IMPACT OF COOL ROOF APPLICATION ON COMMERCIAL BUILDINGS: A CONTRIBUTION TO SUSTAINABLE DESIGN IN AUSTRALIA

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Abstract

The specification of material used in the building envelope has a great impact on the amount of energy usage and thermal comfort inside the building and also on open spaces. Cool materials are characterized by high solar reflectance values, which reduce the solar radiation absorbed by conventional building materials and limit the surface temperature rise under high solar loads. These materials, which are applied to the roof surface for reducing heat gain into the building, are known as ‘cool roofs’. Cool roof technology benefits can be divided into different categories including urban heat island mitigation, reduction of cooling load, peak energy demand, CO_2 emissions, and increase of roof lifetime.

Application of cool roof technology has been started in Australia recently. The number of studies for different types of building in the Australian climate is very limited. Energy saving in commercial and industrial buildings has a great impact on total energy use of developed cities. Improving the energy efficiency of these types of buildings is important. Therefore, this study investigated the cool roof technology effects on annual energy saving of a large-one-storey commercial building (a building in the Arndale shopping centre) in Australia, QLD. The model of the case study was developed in IES-VE software by using the appropriate geometrical and thermal building specifications. IES-VE was chosen for developing the model because it showed an excellent potential for building simulation application in different literature as well as the availability of the software for this study. The field study data from two phases of before and after cool roof coating was used to set-up and validate the model.

To analyse the effect of cool roof technology on the case study, some results were predicted by IES-VE software for different conditions assumed for the case study building. Then, extrapolation of the results to the larger scale in Australia for different cities in various climate zones was investigated. CO_2 emission reductions as achieved by energy saving from cool roof technology in each city were then calculated. Lastly, some information was provided for this type of building (one-storey commercial building) as one step to provide a guideline of cool roof technology use throughout Australia.

It was found that annual cooling energy consumption is significantly reduced between 5.4% (reduced from 57.03 to 53.99 MWh) to 18% (reduced from 16.95 to 13.93 MWh) in the case study building depends on its operational condition, especially infiltration rate, by cool roof application. The amount of annual energy consumption before cool roof coating was reduced by 70% (reduced from 57.09 to 16.95MWh) if the building infiltration rate were changed to the level stipulated in the Green Star retail tool (0.33 ACH@50 Pa) in the case study model. The energy use reduction in different cities varied between 7% (reduced from 47.83 to 44.38 MWh) to 30% (reduced from 6.95 to 4.93 MWh) by cool roof application and these percentages were found to increase to 11% (reduced from 31.65 to 28.11 MWh) to 39% (reduced from 6.60 to 4.05 MWh) if the building infiltration rate were changed to target air leakage (0.33 ACH@50 Pa). The CO_2 emission reduction resulted by cooling energy saving was calculated based on emission factors specialised for each state in Australia for buildings with two different air infiltration rates. The values correspond to taking about three and four vehicles out of the road each year. This study was the initial step towards design of a guideline for cool roof application in Australia.

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List of Abbreviations

IES-VE	Integrated Environmental Solution-Virtual Environment
BCA	Building Code of Australia
NCCA	National Construction Code of Australia
BOM	Bureau of Meteorology
HVAC	Heating, Ventilation And Cooling
ACH	Air Change per Hour
TMY2	Typical Meteorological Year 2

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

QUT Verified Signature

Signature:

Date: 11/11/2015

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Chapter 1: Introduction

1.1 MOTIVATION AND SIGNIFICANCE

In light of the worldwide increased growth of energy consumption, it is imperative to consider its impact on the limited resources, supply problems and environmental impacts such as global warming, climate change and greenhouse emissions. Given this, governments are becoming increasingly aware of the significant energy consumption in the building sector and have responded by implementing policies to address energy efficiency within the built environment. Moreover, applying the best energy efficiency strategies in terms of reducing energy consumption and energy cost is one of the most important challenges for engineers and building designers. Application of new techniques for energy efficiency in the building industry becomes a primary goal in energy policy at both the national and international levels. Large buildings, such as commercial or industrial buildings, are amongst the highest energy consumers in the world and their number has increased between 20%-40% in developed countries. Applying new strategies of energy efficiency in these sorts of buildings could be beneficial in terms of energy use reduction. Cool roof technology is one of the techniques which are useful for reducing energy consumption and improving thermal comfort in buildings, especially for those buildings with large sun-exposed roof area in relation to internal volume of the building.

Cool roofs are designed to maintain a lower roof temperature than traditional roofs while the sun is shining. Cool roofs have surfaces reflecting a wider range of solar radiation spectrum and emit heat more efficiently than hot or dark roofs, keeping the building cooler in the sun. A cool roof surface has a high reflectance and emittance and low absorption characteristics (e.g. a standard black material has the reflectance of 0.05 and emittance of 0.9 while these values are 0.8 and 0.9 for a standard white material respectively). Therefore, cool roof act like a barrier which does not allow the heat to enter the building, thus the building remains cooler in the sun compared to buildings with high absorptive roofs. A wide range of studies about cool roof application have been done in the past, some of which will be discussed in the literature review chapter.

In Australia, many commercial, industrial and retail store buildings have large-one-storey typology which has the best potential to profit from cool roof technology. This study intends to investigate the potential energy savings of cool roof technology applied to commercial buildings specifically one storey buildings in Australia. It will be conducted on an operational case study commercial building (a building in Arndale shopping centre). The monitoring for the case study will be carried out in two phases: ‘before’ and ‘after’ cool roof coating and the actual data including temperature and energy consumption will be obtained. A model of the building will be created using the simulation software package (IES-VE), utilising available or assumed information about building characteristics. To move forward in the project, the simulation results will be verified with actual data variants for the case study. Then extrapolation of the obtained results for the large scale application in Australia is the next specific step in this project. This study reports the results of cool roof application in two aspects: temperature reduction and saving in energy consumption. The analysis gave interesting results on the energy efficiency and thermal comfort potential of this technique for Australian climatic conditions. The results obtained from this study can be used to develop a guideline of cool roof application in large scale in Australia.

1.2 RESEARCH PROBLEM

As will be discussed in the literature review, the main gaps revealed in the literature review are:

- No academic research has been carried out to evaluate the potential of cool roof application in different climate zones of Australia and no peer reviewed paper has been published.
- IES-VE software package has not been used for energy analysis of cool roof applications in the past.
- The extent of potential benefit of applying cool roof on this particular type of building (one-storey large commercial building) in different climate zones of Australia has not been quantified yet.

This study intends to focus on quantifying the extent of the potential benefits of applying cool roofs on a particular type of commercial buildings, namely large, one-storey buildings, this building type has perhaps the greatest potential to benefit from this technology, in Australian tropical or subtropical climates. To approach this goal, the IES-VE simulation software will be utilized for analysis.

The main objectives of this research are:

- Developing a computer-based simulation for the building in the Arndale shopping centre and validating the developed model by using the existing field study data.
- Analysing the effect of cool roof application for the building in the Arndale shopping centre in Brisbane's climate condition.
- Generalizing the simulation results to evaluate the effect of cool roof application on similar buildings in different climate zones of Australia.
- Approaching to some information about cool roof technology use in Australia that could contribute to a guideline.

Specific research questions in this area will include:

- What factors are important in the case study for computer modelling?
- What is the accuracy of IES-VE software for cool roof simulation and how can it be effectively used to examine the energy use?
- How much energy savings does a commercial building accomplish with the application of cool roof in Brisbane?
- How is energy consumption affected by the cool roof application on the same type of commercial building in different zones of Australia?

This study follows a methodology that combines both field study and software modelling to investigate the electricity savings and thermal comfort conditions that could be achieved with the application of a cool roof system in Australia. The research has two main phases. The first is simulation and validation using experimental data. The second is analysis of cool roof technology in the case study and the same commercial building in different climate zones in Australia using the validated model. The field study data for before and after installation of cool roof on a commercial building in Brisbane is used to develop the simulation. The measurement represents the actual savings resulting from the application of the cool roof strategy. After developing and validating the simulation in IES-VE the temperature reduction in the ceiling void of the current case study and energy saving for different operating condition of the case study is predicted. Moreover, extrapolating the results for case study in different climate zones of Australia is considered. Where required, appropriate assumption and estimations will be made to best represent the actual operating conditions, based on available information.

1.3 THESIS OUTLINE

This thesis consists of five chapters:

Chapter 1-Introduction: In the first chapter, an introduction to the project subject is presented and aims, objectives and research problems are discussed.

Chapter 2-Literature review: This chapter gives an extensive literature review and analysis of the research subjects. The literature on the role of roofs in sustainability, cool roof technology, the benefit of cool roof applications, simulations methods and IES-VE software are reviewed in this chapter.

Chapter 3-Methodology: The concept map is introduced in this chapter and shows the different steps in the progression of this project. It then introduces the case study (a building in the Arndale shopping centre) and presents the detailed methodology applied in this research. The building plans and construction material are delineated based on available or assumed information. Shortage of information about this building is discussed and the methods for simulation and validation are explained. Lastly, the method for extrapolating the results to the different climate zones of Australia will discussed.

Chapter 4-Results and discussion: The final results of this research are presented in chapter 4. The validation process and all the important factors including for model validation are discussed in detail. All the findings including energy savings for the case study in different operational conditions and CO_2 emission reduction are presented. Furthermore, the extrapolations of the results in Australia are discussed and the potential of the cool roof application in different locations are illustrated.

Chapter 5-Conclusion and future research: In this chapter, a summary of the relevant literature, the applied methodology, the results and the discussion of this research are presented and further plans for future studies of cool roofs will be expressed.

Chapter 2: Literature review

2.1 OVERVIEW

This chapter analyses the current literature according to the five important themes for this project: the role of the roof in sustainability, cool roof technology, cool roof case studies, simulation methods for cool roof evaluation and the selected simulation software package (IES-VE). There is extensive literature which is discussed on each theme. The following review investigates the literature for identifying the necessity of conducting this research as well as identifying current gaps for further research and knowledge improvement within this field.

2.2 THE ROLE OF ROOFS IN SUSTAINABILITY

Cooling loads inside a building depend partially on occupant body heat, lighting appliances and, electrical and gas equipment inside the building. However, the main cooling load inside a building comes from the solar heat gain through walls, windows, floors and ceilings [1]. Roofs play a key role in both internal and external comfort. Roofs are exposed to the sun more than other parts of a building. Since they are vast and mostly horizontal (especially in tropical and subtropical climates), they noticeably effect internal temperature and comfort levels [2]. Some research estimate that roofs account for more than 20% of total urban area [3]. Therefore, roofs can provide a good potential for applying heat mitigation techniques to reduce the cooling demands and greenhouse gas emissions.

Another key influence of roofs is the impact on the larger urban space through the heat island and microclimate effects. Heat island is defined as the increase of urban temperatures compared to the suburban area, which may reach values close to 10ºC [4]. Microclimates are formed due to the building replacing the natural environment resulting in change of the wind movement pattern and/or the water and energy exchanges model [5]. The importance of these two phenomenon can be understood better when we know that more than 50% of the world's population live in cities now, and this ratio will reach about 70% by 2040, which can have a major effect on global and local climate [6]. Therefore, considering sustainable building design strategies can provide a great potential for energy saving and decreasing the overall environmental side effects. The effectiveness of cool roof also varies in different climate zones. Figure 1 represents the distribution of different climate zones across the world.

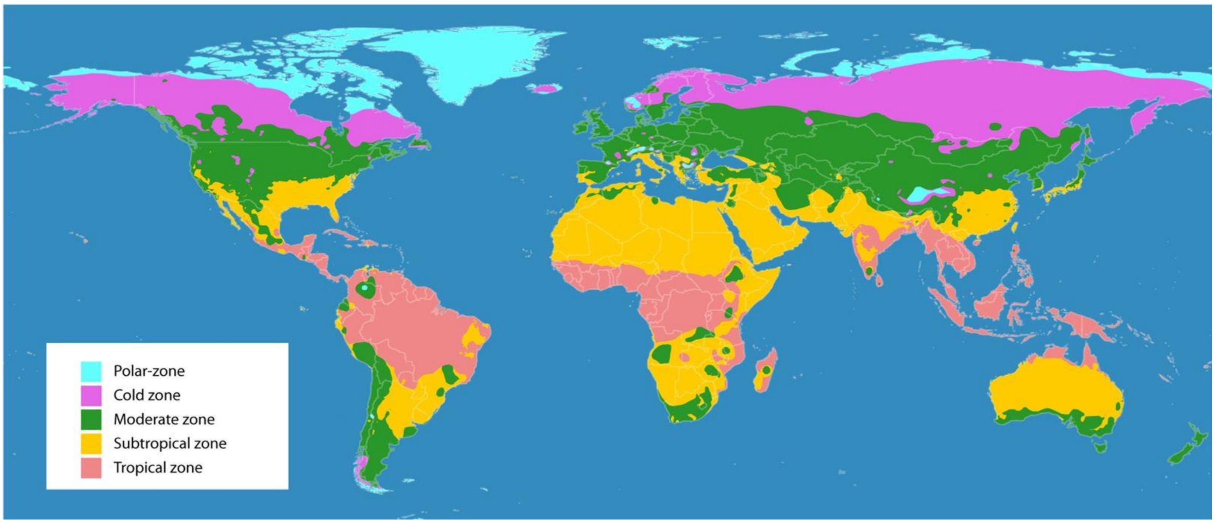


Figure 1.The world climate map [7].

Different rooftop technologies have been considered for decreasing storm water runoff, electricity generation, building energy consumption reduction, or mitigating the urban heat island effect (UHI) [8]. Among different possibilities for roof applications, cool and green roof technologies attract more attention than other heat island mitigation technologies, while the overall energy efficiency of these two technologies depends mainly on the climatic conditions and the constructional characteristics [4]. From a heat transfer point of view, there are three possibilities to decrease the heat gain from roofs including the use of roof insulation, shading the roof surface and, cool roofs [1, 5].

2.3 COOL ROOF TECHNOLOGY

The typical albedo of a roof ranges from 0.06 (dark black) to 0.83 (high albedo white). The solar absorptance and reflectivity of a roof will change with time due to dust and aging [9]. The albedo can be restored to about 90% of its original value if the roof is washed [8, 10] Cool roof technology has been developed based on the theory of using reflective materials in buildings. High reflectance and high emittance coatings or paintings applied to the roof surface for reducing heat gain into the building are known as ‘cool roofs’ [11]. The criteria for defining a cool roof are a minimum solar reflectance and minimum thermal emittance of 0.70 and 0.75, respectively and aged solar reflectance should not be less than 0.55. As an exception, the solar reflectance criterion for tile roofs should be about 0.40 [12]. Most of the cool roof studies and applications have focused on cool paints and membranes implemented over flat roofs as the most economical and easy way to apply cool roof technology [13, 14]. Synnefa et al. reported different cool coating and painting materials for commercial cool roof applications [15-17]. Cool roof material is typically white with high albedo and it is single ply or liquid applied coating. Typical liquid coating materials for cool roof application are white paints, elastomeric, polyurethane or acrylic coatings. Examples of white single ply products involve EPDM (Ethylene-Propylene diene-Tetrolymer Membrane), PVC (Polyvinyl Chloride), CPE (Chlorinated Polyethylene), CPSE (Chlorosulfonated Polyethylene), and TPO (Thermoplastic Polyolefin) materials [18, 19]. The construction material affect the urban's temperature and it is important to choose the appropriate material in the urban buildings and cities. A comprehensive study on the performance of urban building materials can be found in [20].

Infrared and solar energy are absorbed by the construction materials in buildings while a portion of absorbed heat can be transferred to the atmosphere through the re-radiation and/or convection heat transfer. Therefore, the specifications of material used in the building envelope has a great impact on the amount of energy usage and thermal comfort inside the building and also on open spaces [14]. Cool materials are considered as a passive technology. With low cost and low environmental impact, they are characterized by two factors: high solar reflectance and high infrared emittance. The temperature of a surface depends on these two characteristics which are discussed in Figure 2 [10, 14, 21]:

- High solar reflectance (SR): Solar reflectance is the criterion to characterise the amount of the solar reflectance from a surface measured in the range of 0 to 1 (or 0–100%).
- High infrared emittance (e): Infrared emittance is a criterion to evaluate the capability of a surface to gain or reject the heat compared to a black body. It is changing in the scale of 0 to 1 for each material. The range of wavelength is about 5 to 40 µm for this emitting energy.

Cool materials stay cool under the solar radiation. They are characterized by high solar reflectance values. These reduce the solar radiation absorbed by conventional building materials and thereby limiting the surface temperature increase under high solar loads. These materials are also characterized by high infrared emittance values being able to emit to the sky during the night and dissipating the gathered heat without transferring it indoors [22].

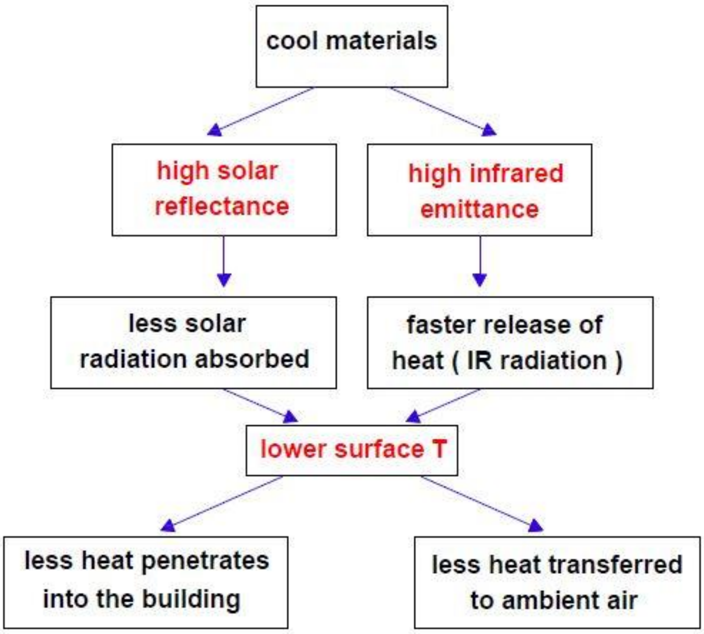


Figure 2. The basic principles of cool materials [14].

Cool roofs decrease urban solar heat gain by increasing the solar reflectance of the roof surface which results in surface temperature reduction and its outflow thermal radiation into the space [23]. This effect can help to reduce the global warming influences and urban heat islands. Moreover, by increasing the number of cool roofs in urban areas, the cooling load will be reduced directly due to the reduction of heat gain, and indirectly due to the reduction in overall urban air temperature [24, 25]. In analysing the heat island effect, it is common to consider the heat flux which is defined as the rate of heat transfer per unit of area. Replacing a black roof by a white roof, can reduce the peak heat flux by about 70% and the total daily heat flux by about 80% [8]. The cool roof temperature is slightly higher than the air temperature during the day while the difference between the air temperatures and a dark roofs temperature is highly different [22]. Usually, the increase in temperature of a typical roof is much higher than the surrounding temperature increase on hot days of summer. However, using the cool roof can reduce the peak roof surface temperature by 33–42ºC [26]. Cool roofs can moderate peak electricity demand during the summer days when the heat gain is increasing in the middle of the day until late afternoon because it decreases the space temperature [27]. In buildings without air conditioning system, the lower heat transfer into the building resulting from cool roof application lowers internal temperatures, improving thermal comfort. Indoor temperature reductions of between 1 to 2.7 ºC have been reported in different experimental and simulation results in literature [28-31].

The thermal conductivity of insulation (R-value) decreases when the delta T, the temperature difference on either side of the insulation, increases (e.g. by increase of 17ºC in temperature, heat transfer increases by 15%) [32]. By employing cool roof technology this effect can also be avoided. Furthermore, the roof absorbance and reflectivity will change because of dust and aging over time. Thus, some course of action must be done to maintain the roof characteristics as its initial condition [8, 10] while this effect has been reduced in the newer cool roof technologies[33]. Reflective materials also have the potential to extend roofing lifetime due to the reduction of environmental stresses such as temperature cycling by sunlight, sharp temperature variation (e.g. because of the rain) and corrosion due to the moisture penetration [34].

There is an inverse relationship between the amount of roof insulation and the effectiveness of cool roof technique: large energy savings can be achieved if we consider this technique for poorly insulated buildings [24]. Moreover, cool roof applications are more effective in buildings located in climates with long hot seasons, especially those buildings with distributed cooling ducts in the plenum [12]. The most significant positive results with cool roof technology are related to the high ratio of the roof surface to the building volume. Generally, it should be mentioned that the impact of cool roofs will decrease with the reduction of the above ratio and lower relative savings are projected for multi-storey buildings, while the specific savings, typically measured based on roof area in square metres, will not change significantly [22].

Reducing the temperature of the roof with this technique can also increase the heating load during cold seasons [35]. If the heating loads in cold seasons are higher than the cooling loads in warm seasons it does not necessarily mean that cool roof application is not beneficial. In this case, the price of the heating source (e.g. gas or electricity) should be considered. It is highlighted in the literature that for locations without heating needs, a cool roof solution can be the optimal option [35, 36]. Previous studies indicate that net annual energy cost savings are greater for long cooling seasons and short heating seasons [11, 27]. This means cooling load reduction due to the cool roof application in hot and moderate climates (Figure 1) is much higher than the heat load penalty [28, 29, 37].

Akbari et al. [23, 38] showed that the widespread application of cool roofs and cool pavements helps to mitigate summer urban heat islands, thereby further reducing the overall air conditioning load due to improving outdoor air quality and comfort. Cool roof technique is a low-cost method and passive solution to reduce the cooling loads in air-conditioned buildings and improve the indoor thermal comfort conditions in non-air conditioned residential buildings especially in hot climates [29, 39, 40]. Voluntary motivations and/or compulsory regulations were two courses of action that several societies have used to develop cool roof programs. In 1995, Georgia State was the first place in which the cool roof characteristics were approved as a part of the energy code in the USA. The building energy code in Chicago was modified for application of cool roof in low-sloped roofs by January 2003, and by introducing Title 24 building code in California, the cool roofing option was added to standards to overcome the electrical energy deficit in 2001. Cool roof provision has become compulsory all over the United States since 2005 for all new-build non-residential buildings and for 50% or more of roof substitutions on old buildings with more than 90 m^2 roof area [5, 41].

As discussed above, cool roofs are as a low-cost and easily applicable technology and an effective solution for the reduction of energy requirements for cooling and mitigating the urban heat island especially in hot and moderate climates [1, 42]. The main key knowledge about cool roof technology is:

- Higher ratio of the roof surface to the building volume, increase the impact of cool roof technology [22]. This means it is beneficial for single-storey, large, flat-roofed buildings such as commercial or industrial buildings in Queensland.
- Cool roof technology is more cost effective in climates with long cooling seasons and short heating seasons. However, for other climates with different conditions, the price of the heating source (gas or electricity) should be considered to evaluate whether this technique is beneficial or not from a cost perspective [35, 36].
- Indoor temperature reduction, thermal comfort improvement, and decrease of cooling loads are all possible energy efficiency benefits of using cool roof technology [24].
- Use of cool roof systems will decrease the heat input into the building and reduce the temperature of the ambient air and the heat island effect [22].
- Energy savings are higher for lower insulated roofs [24].
- Cool paints and membranes implemented over flat roofs are the most economical and easy to apply on different types of buildings [13, 14].

- Since roofing material, weathers and collects dust via aging, some course of action must be taken to maintain cool roof characteristics (solar reflectance and infrared emittance) as close as possible to initial condition [8, 10].

2.4 REVIEW OF COOL ROOF CASE STUDIES

Cool roof benefits can be divided into different categories including urban heat island mitigation, reduction of cooling load, peak energy demand, CO_2 emissions, and increase of roof lifetime. In this section, a quantitative review of cool roof benefits from different literature has been considered and the results of different publications have been analysed [18].

Between 20% and 95% of solar radiation will typically be absorbed by the conventional roofs during a clear sky condition and the temperature of these roofs can get to over 60°C on summer days [1, 5, 9]. Therefore, highly reflective materials (in the infrared wave length) can be used for cool roof applications. By using high solar reflectance coating on conventional roof materials or replacing them by high reflective materials, roof temperature, and, correspondingly heat transfer through the roof, can be controlled. For example, the study of cool roof coating for different roof colours revealed that the maximum solar reflectance difference between a cool and conventional colour matched coating was for a black colour roof [29, 43]. In this case, the solar reflectance difference was around 22 which resulted in 10.2°C temperature difference [29, 43]. Furthermore, increasing the solar reflectance of roof material such as asphalt shingles, tiles, metal roofing, wood shakes, membranes, and coatings by using cool pigment during their manufacturing process was reported in [44]. It was shown that by using the cool pigments, solar reflectance of conventional materials increases from 0.05-0.25 to 0.3-0.45 which provides the great potential for energy saving.

The early research about application of cool roof has been conducted in the United States. Table 1 summarises a number of research on residential and non-residential buildings in this area.

Table 1. Overview of energy savings by using cool roof in different buildings.

Research Team	Year	Location	Energy saving	Peak demand reduction	Climate zone	comment
Boutwell and Salinas 1986 [31]	1986	Mississippi	22%	Not reported	Subtropical	No penalty in winter
Parker and Center [30]	1993	Florida	10% - 43 %	16-38%	Subtropical	Experiment with different high albedo materials
Akbari et.al [16, 34]	1997	Sacramento	40-50%	30- 40%	Subtropical	High albedo materials on several buildings
Akbari et al. [11]	1998	Two medical office in (Davis and Gilroy), one retail store (San Joze)	18%, 13% and 2%, respectively	12%, 8% and 9%, respectively	Moderate	The daily cooling energy saving was found to be 67, 39 and 4 Wh/m^2, respectively

Hildebrandt et al. [45]	1998	An office, a museum and a hospice building in Sacramento	17%, 26% and 39%, respectively	Not reported	Moderate	The daily cooling energy saving 23, 44 and 25 Wh/m^2, respectively
Konopacki and Akbari [46].	2001	Retail store in Austin	11%	14%	Subtropical	Daily energy saving and peak power demand per m^2 were 39 Wh/m^2 and 3.8 W/m^2
Akbari et al. [24].	1997	Single-storey and flat-roofed house in Sacramento	80%	30%	Moderate	Solar reflectance increased from 0.18 to 0.7- energy saving and peak power demand reduction of 14 Wh/m^2 and 3.8 W/m^2
Parker et al. [47].	1998	11 residential building in Florida	Ranging from 0.2% to 45%	Not reported	Subtropical	Solar reflectance increased from 0.08 to 0.7
Parker [36].	1998	A school building in Florida	25%	30%	Subtropical	Energy saving and peak power demand reduction of 44 Wh/m^2 and 6W/m^2, respectively. An aged solar reflectance was assumed to be 0.55.

The benefits of cool roofs are not limited to hot climates. For a flat roof office building in the moderate climate of suburban London, cool roof application could improve thermal comfort in summer and reduce overall energy usage [48]. For this naturally ventilated building, thermal comfort temperature was found to decrease about 2.5°C while a 10% increase in heating demand on winter was reported. Total energy saving amount varied between 1% and 8.5% depending on set-point temperature. Roof insulation was found to be an important parameter for decreasing the heat and cold demands. The amount of energy saving was higher for lower insulated roofs [48]. In a simulation case study of a small cabin, it was shown that the reflective interiors (coating inner claddings with low thermal emissivity material) is more effective for cold climates and reflective exteriors (coating outer claddings with low thermal emissivity material) is more effective in warm climates; moreover, the combination of both reflective interior and exterior is the best option for mild climates [49]. In another study for a building located in central Italy with 70% cooling energy share from the total building energy consumption, the heating penalty in winter was less than one third of the cooling reduction benefit in summer by using cool clay tile on the roof [13]. Zinzi and Agnoli [40] compared the effect of cool and green roof energy performance by using a numerical dynamic simulation in different localities at Mediterranean basin. They found cool roof technology more effective for the centre and southern areas of the Mediterranean latitudes. They showed that implementation of cool roof technique in residential buildings can decrease the number of hours for internal temperature above 28°C by more than 80% [13, 40] . Bozonnet and Allard [50] studied the effect of cool roof on a moderate climate case study in France by considering the experimental results and developing a dynamic model. They found a decrease of more than 10°C on the mean outside surface temperature with higher differences for the higher temperatures.

Pisello et al. [13] evaluated the thermal performance of cool roof technology by using a high-reflectance clay tile in a residential building in Italy. They monitored the thermal performance data of this house for two years from coupled indoor microclimate monitoring stations and outdoor weather monitoring stations installed for this study. They found that their proposed cool roof technique reduced the summer peak indoor overheating by about 4.7°C for the attic while the corresponding winter maximum overcooling was reduced by 1.2°C. Boixo et al. [51] considered the possibility of annual saving by application of cool roofs in Spain. They recommended that this technology should be encouraged even in that region and they estimated an energy saving of 295,000 kWh per year, by implementation of cool roofs in only residential buildings with flat roofs in the south of Spain.

The cool roof application has been evaluated for large scale applications as well. Akbari and Rose [52] estimated the roof area fraction to be 20% for low dense cities and 25% for high dense cities in USA by using resolution orthophotos. They estimated that by increasing solar reflectance of total roofs by 0.25 (the initial value was assumed to be 0.25) and paved surfaces by 0.15 (the initial value was assumed to be 0.35), the global CO_2 reduction of 44 Gt can be achieved because of drop in average ambient temperature in urban environment and less solar radiation absorption [3, 23]. Menon et al. [53] developed a simulation by use of the land component (CLSM) of the NASA GEOS to study the effect of increase in albedo of roofs and pavements in urban areas. They found that an increase of 0.0003 in surface albedo, resulted in the land surface temperature reduction about 0.008ºC. In a recent study, Akbari et al. [23] estimated that by developing cool roofs and cool pavements, the average albedo of an urban area can increase about 0.1. This increase, results in reduction of CO_2 emission by at least 40-160 Gt worldwide. In another study, Jo et al. [1] simulated the potential benefits of urban scale implementation of cool roofs on 932 commercial and government buildings. They found that 73% of buildings have had the reflectivity of below 0.4 and cool roof implementation can reduce electricity usage by 4.3% (7830 MWh) annually.

Bhatia et al. [54] developed a simulation technique to evaluate the effect of cool roofs in five Indian climatic zones. They found that the effectiveness of cool roof techniques varies with climate condition significantly. While the maximum energy saving were obtained for warm and humid climatic zones, the amount of energy saving in hot and dry, temperate, and composite climatic zones was considerable as well. The financial payback period for hot and cold zones was reported to be about 3 and 6.7 years, respectively. They found a significant variation in the amount of energy savings in different months; however, the maximum energy saving was between March and May which are the hot months. They concluded that the cool roof application is beneficial in warm and humid, hot and dry, and temperate climatic zones while for the composite climatic zone, its benefit is less than those three zones. For considering cool roofs in cold climate zone, a detail analysis of internal heat gain and cooling requirement thereon has been recommended by them [54].

Synnefa et al. [29] developed a simulation model for a flat-roof residential house for 27 cities around the world (such as Abu Dhabi (UEA), Ankara (Turkey), Athens (Greece), Johannesburg (South Africa), Tokyo (Japan) etc.). They evaluated the effect of cool roof on thermal comfort and cooling and heating energy demand. They showed that the cooling demand can be decreased from 18% to 93% and discomfort hours can be reduced from 9% to 100% in different climate conditions while the heating penalty in cold climates was lower than the cooling benefits. Haberl and Cho [20] evaluated the effect of cool roofs material in different literature. Based on their literature review, the energy savings vary between 2% to 44% and averaged about 20% for different commercial and residential buildings and peak cooling energy saving from 3% and 35% depending on attic configuration, insulation level and duct placement [28].

Akbari et al. [26] expanded the existing data of cool roof application in a school building, a fruit packing facility and a retail store to estimate the amount of energy savings by installing similar cool roof material in 16 California climate zones. They found energy saving of 3 to 6 kWh/m^2/year of conditioned roof area and they reported additional benefits such as lowering air temperature due to the increase of urban albedo, heat island effect mitigation and increase life time of roofs and reduction of maintenance needs. Akbari et al. [38] studied the effect of cool roof on annual cooling energy saving for a prototype house for different cooling-dominant cities. The amount of savings varied from 700 kWh/year for hot climates to 170 kWh/year for mild climates. In another study they calculated the effect of cool roof on a prototype office building in the same cities and reported energy savings of 500 kWh/year for mild climates and over 1000 kWh/year for very hot climates. Assuming energy cost of US$0.10/kWh and a 20-year life for a roof, they calculated the energy saving of US$3.7–15/m^2 of roof area [3]. They also discussed the emission saving by considering the rate of 750 g CO_2/kWh of electricity savings which is found to be between 1.9 to 7.5 kg/m^2 of roof area [23]. Levinson and Akbari [27] simulated the potential benefits of cool roof application for commercial buildings in 236 US cities. They suggested that by retrofitting 80% of the commercial building roofs by reflective white roof (solar reflectance 0.55), annual cooling energy saving of 10.4 TWh, annual heating energy penalty of about 3. 9 TWh; and an annual energy cost saving of US$735 million can be achieved. They considered environmental benefits which were equivalent to annual CO_2 reduction of 6.23 Mt. In addition, annual reduction in emission of NO_x, SO_2 and Hg equivalent to 9.93 kt, 25.6 kt and 126 kg were reported, respectively [27].

As it is shown in various literatures, cool roof applications are beneficial from different perspectives in building applications. In general, cool roofs were found to be more effective in low insulated buildings in different climates [24, 29] due to the reduction of indoor air temperature especially during the hot seasons. For example, old houses with little or no insulation have shown a great potential of energy saving from cool roof applications in different simulation and experimental studies [28, 29, 38]. Application of cool roofs in different buildings can provide the opportunity of a great saving in energy bills and can provide the possibility of better performance for cooling systems especially in large buildings with high cooling load demands such as industrial buildings and supermarkets [32]. Moreover, the application of cool roofs on large scale, especially for dense urban environments, can result in reduction of outdoor temperature and provide passive cooling such as natural ventilation and night cooling for non-air-conditioned dwellings [50]. Finally, an increase in the life-expectancy of roof materials can be obtained due to the considerable reduction of the surface temperatures by using cool roofing products on roofs [55].

Key points from the literature can be highlighted as follow:

- Cool roof technology assists urban heat island mitigation, reduces cooling load and peak energy demand, increases thermal comfort, reduces CO_2 emissions (in typical fossil fuel powered air conditioning), and increases roof lifespan [18].
- Cool roof technology has different levels of effectiveness depending on the climatic zone, with warm and humid climates experiencing the largest benefit, followed by hot and dry, and lastly, temperate climates.
- A high percent of energy saving and peak power demand reduction can be achieved for single-storey and flat-roofed cases [24, 29].
- Financial payback period varied with climate zone and country. For hot and cold climate zones in India, a payback period of about 3 and 6.7 years was reported, respectively [54].
- For air-conditioned cases, energy savings depended on the internal set-point temperature.
- Although the percent of energy savings for buildings was sometimes not as significant as anticipated, the amount of energy saving remains significant when expressed in terms of energy savings (eg.11% is 39 Wh/m^2 for daily energy saving in a retail space in the US, while 14Wh/m^2 represents a daily energy saving of 80% in a flat-roofed house in the USA) [12, 24, 46].

- For commercial buildings the range of energy savings associated with cooling varies between 3.3 kWh/m2 for Alaska and 7.69 kWh/m2 for Arizona which highlights the importance of energy savings in commercial buildings [27].
- Commercial buildings have the potential to have a significant impact on the environment (reduced heat island effect, increased energy efficiency and hence reduced CO_2 emissions, NO_x emissions, SO_2 emissions and Hg reduction) if cool roof technology is installed on 80% of current building stock in the USA [56].
- Cool roofs act to reduce thermal stresses within the roof, that may act to increase the lifetime of the roof while reducing maintenance such as re-reroofing and the associated waste [38].

2.5 SIMULATION METHODS FOR COOL ROOF EVALUATION

Both experimental and simulation techniques are used to evaluate the application of cool roofs. In experimental methods, the climatic and operational data such as air or surface temperature, cooling and heating energy consumption, thermal conductivity, solar gain and surface reflectance should be collected and after conducting the data analysis, the real life results can be obtained [14, 39, 57, 58]. However, the key disadvantages of using experimental methods for evaluating cool roof applications can be the high cost of experiments and long-time duration requirement. Moreover, these techniques are not applicable in the design phase to evaluate different scenarios. To overcome this problem, computer simulation methods have been used widely in different building applications [59-62]. Computer simulation techniques provide a variety of advantages due to the accessibility of low-cost high-performance computers and accurate simulation software. By using the simulation software, different parameters can be easily changed and optimized under a controlled environment and a lot of time can be saved depending on the problem size and required accuracy. However, the validity of the simulation depends on the accuracy level of software, robustness of the calibration process and the proficiency of the user. To investigate the methodology of different publications using simulation software, a number of examples are discussed below.

Synnefa et al. [28] simulated the effect of increasing the reflectance on a non-cooled school roof by using TRNSYS software and calibrated their model with experimental data. The schematic plan of this school building is shown in Figure 3. It was a two storey building built in 1988 with the roof area of 410 m^2 and the gross floor area of 939 m^2. This school used water heating with radiators for heating while there was no cooling or ventilation system. They used temperature set point of 20°C for heating of the classrooms and 18°C for the offices and corridors. There was a small fan in teachers' office and natural ventilation was used for cooling purposes by opening the windows and cooling set point temperature was considered to be to be 26°C. Roof solar reflectance was 0.2 at first and then a white elastomeric water proof coating with solar reflectance value of 0.89 was applied as the cool roof technology.

Figure 3. School building lay-out and zoning [28].

They conducted onsite measurement campaigns and recorded air temperature, relative humidity and surface temperature. Different thermometers were installed inside and outside of the building to collect air temperature and relative humidity data. The thermometers were located in three classrooms adjacent to the roof on the first floor, in teachers' office and one thermometer outside the building. Furthermore, the roof surface temperature was measured by using infrared thermometer. These measurements were conducted on a number of spots on roof top every hour from 9:00 to 18:00 on selected days and the average of these data was calculated. The hourly value of outdoor temperature, outdoor humidity, solar radiation (total and diffuse), wind speed and direction were obtained from meteorological data of a nearby meteorological station. The measurements were performed in two different time periods: before application of cool roof coating (in October 2007) and, after application of cool roof (from 15th May to 30th September 2009). As mentioned before, they developed their model by using TRNSYS software. To set their model and perform fine tuning, they compared the experimentally collected indoor air temperatures with indoor air temperatures calculated by the software. The model was set up by considering the energy systems to be switched off and allowing the indoor temperatures to free float. The data set which was used for building and setting up the model was the data prior to cool roof coating and part of the data after cool roof coating (12 July to 31 August 2009). Then, a different data set was considered to check the validity of the model by comparing the results from the model without any further changes with experimental results while the building was fully operational. The results of their model calibration for zone 2 and 7 (see Figure 3), and the measured versus the predicted air temperature and surface temperature of the zone 7 are shown in Figure 4 and Figure 5 respectively.

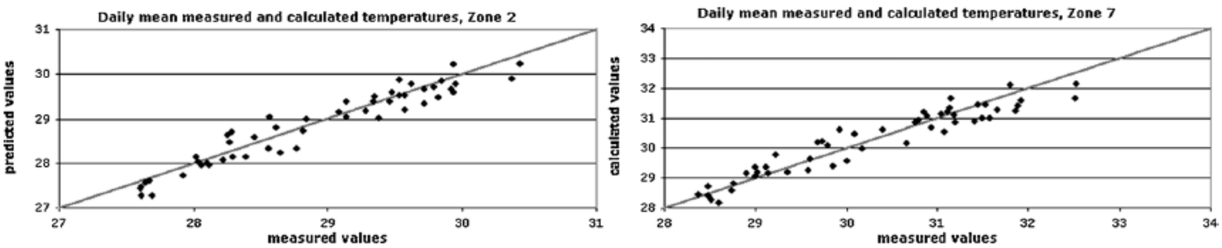


Figure 4. Measured and predicted daily mean air temperatures for zones 2 and 7 [28].

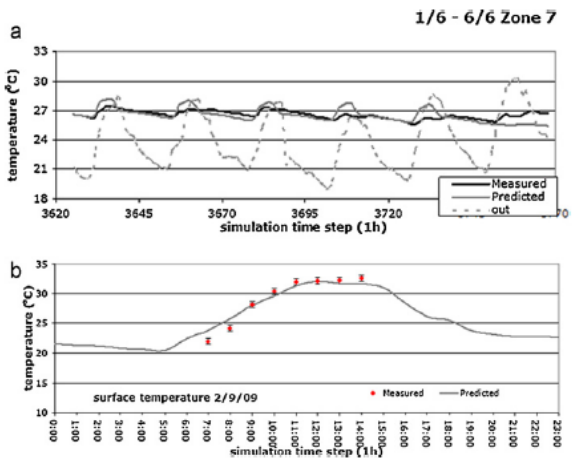


Figure 5. Measured and predicted values of classroom air temperatures after the calibration of the model for the period 1/6/2009–6/6/2009 (A) and predicted and measured values of roof surface temperature on the 2nd September 2009 after the application of the cool roof coating (B) [28].

Jo et al. [5] studied the effect of cool roof application on energy saving and surface temperature reduction. They developed a simulated model and they validated their model by on-site data collection obtained from 40 days of temperature monitoring of the interior and exterior roof surface. In this simulation, surface temperature distribution, energy usage, peak-time electricity demand and the environmental effects were evaluated. To compare the amount of heat gain for original and cool roof, six thermometers on the interior and six thermometers on the exterior of each roof were installed (Figure 6). Loose gravel was used to cover the exterior thermometers to avoid the direct sunlight while these thermometers were connected to the polymer membrane directly. Moreover, by using an Omega four channel data logger surface temperature at two different points, air relative humidity and air temperature was recorded. The interior thermometers and data loggers were located almost directly opposite underneath of the exterior thermometers. To provide enough thermal contact, the interior temperature thermometers were connected to the concrete roof by using a thermal heat transfer paste and adhesive tape. The temperatures on the roof surface and in the adjacent air as well as the relative humidity for both sides of building roof were recorded continuously from 13 August to 19 September 2008 at 30-min intervals. The solar reflectivity was measured at each point for three times on the surface of the roof while the average was considered for each roof side and for two different roofing materials.

The Sensor Network: Outdoor sensors (S1-12); Interior sensors (S13-24)

Figure 6. Image of the entire building roof and the thermometer network. The cool roof section is on the left (east side) and the original roof material on the right [5].

They used Energy Plus software to develop their cool roof simulation due to its capability to deliver the hourly building energy consumption based on user-defined structure, internal energy consumption, schedules, and weather data. The Metrological data such as temperature, humidity, wind, and solar radiation was provided from a station located 16 km north of the site. The software predicts temperatures on the roof surface every 30 min. Electrical usage for every month over the 40 days of collected empirical results has been deployed to ‘tune-up’ the simulation. The thickness of the roof insulation was between 0.05 m (2 in) and 0.13 m (5 in) from the as-built drawing. The thickness of the roof insulation was modified in the simulation model until the surface temperatures from the model and the experimental data agreed. Based on this process, they surmised an insulation thickness of 0.12 m (4.7 in) which relates to an R-value of 27 ft2·°F·h/(BTU·in) (US imperial measurement). The simulated and experimental data for outdoor surface temperature of Roof A and B was found to be in an acceptable range as shown in Figure 7.

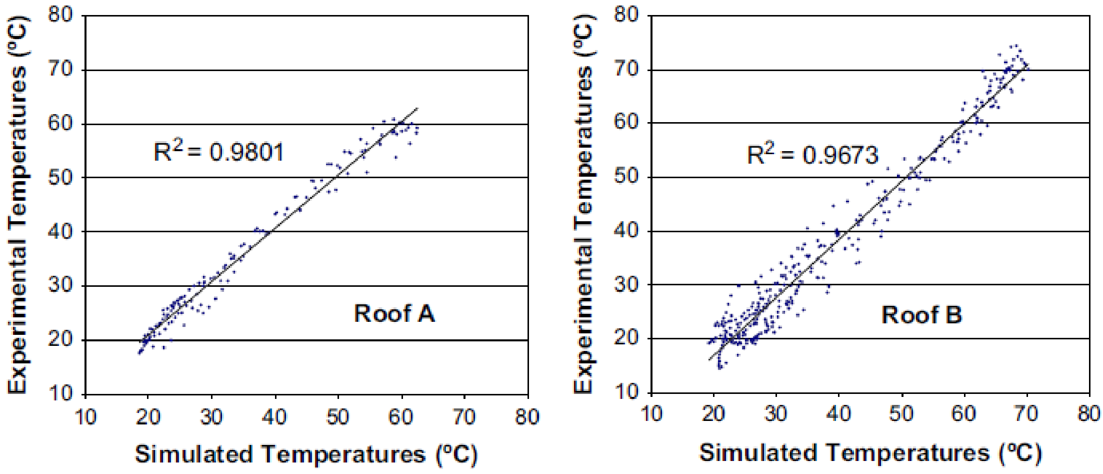


Figure 7. Experimental versus simulated outdoor surface temperatures for Roof A and Roof B [5].

After validating the model, they calculated the interior temperature from simulation as well. They found the experimental and simulation results for Roof B were well matched while the simulation and experimental profiles for Roof A were slightly different as shown in Figure 8. Then the developed model was used for estimating the potential reduction in the monthly electricity demand for three various scenarios:

(1) Baseline simulation which is before cool roof construction

(2) Half of the roof with cool roof material (current condition)

(3) Full cool roof installation (in the future).

Akbari et al. estimated the effect of cool roof on energy load and thermal comfort in different climate condition by developing a simulation model. They developed a simulation by using TRNSYS thermal simulation software for 27 different cities with different climate conditions including Mediterranean, humid continental, subtropical arid and desert conditions. They used METEONORM data base to obtain the meteorological data and they developed an hourly time step simulation. A base case building has been considered in their simulation in different climate conditions. It was a single-storey, flat roof house with a roof area of 100 m^2. Heat input per person was assigned based on ISO7730 and for the artificial lighting and any other equipment, the assumption that 50% each of convective and radiative heats contribute to the input, was made. Other thermal and geometrical specifications and assumptions can be found in their paper. They considered infrared emittance of 0.9 and three different values for roof solar reflectance including 0.2 for the base case, 0.6 for moderate reflectance and 0.85 for extreme reflectance. The goal of their simulation was to find the amount of energy saving and potential heating penalty gain by changing the roof reflectance in different climate conditions. While the modelled building is not necessarily the typical house in all the tested locations, as they mentioned there is no conflict with this issue and their goal of simulation. Their method can be used to extend the result of a simple case study to a wider area of applications.

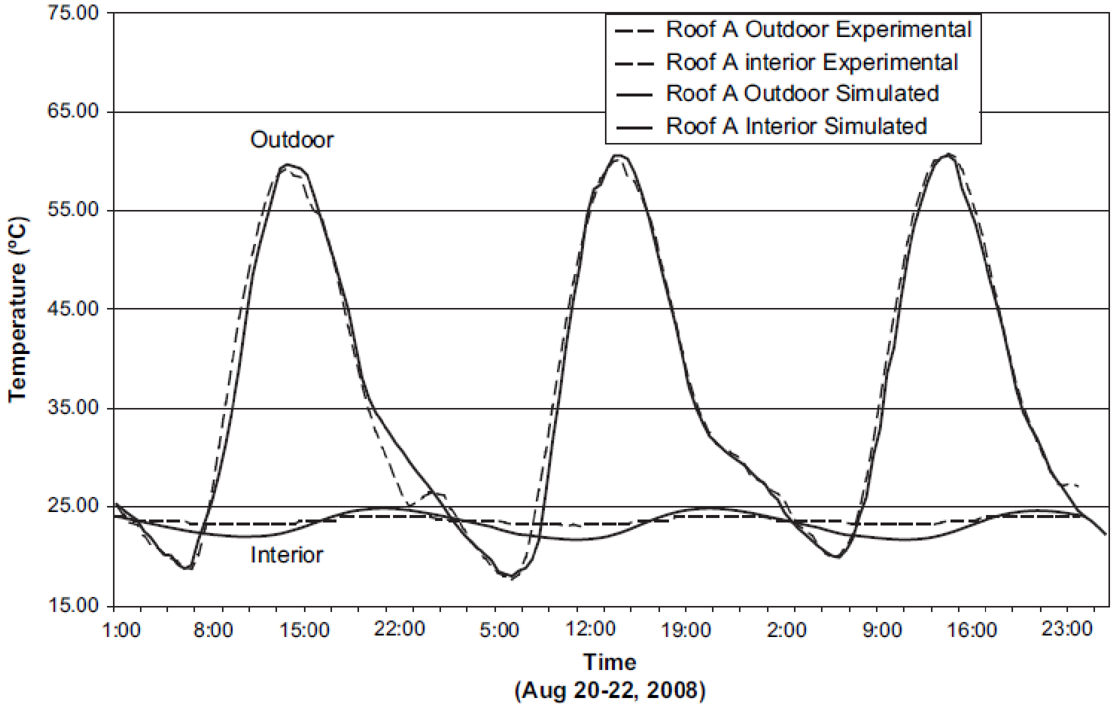


Figure 8. Experimental and simulated surface temperatures for Roof A [5].

As discussed in different publications, the simulation was used effectively for cool roof applications. To set up and validate the model, building characteristics and experimental data should be employed to develop an accurate model. Then, the validated model can be used for prediction and estimation of building performance in various operating conditions.

2.6 INTEGRATED ENVIRONMENTAL SOLUTION SOFTWARE (IES-VE)

There are various software products available for developing a model of building energy performance such as: TRNSYS, EnergyPLus, DOE-2, Ecotect and IES-VE. These different software programs have different capabilities and they can be used in different applications including lighting simulation, ventilation analysis, energy load calculation and CFD analysis. Depending on the complexity of the problem and the availability of the simulation package, researchers can choose the appropriate software to develop building models. IES-VE showed an excellent potential for building simulation application in the past. Attia et al. [63], compared 10 different energy simulation programs by conducting a survey mainly from an architects, designers, architecture educators and students perspective and their results were shown in Figure 9. As can be seen, IES-VE showed the best record among the respondents considering criteria such as: the usability and information management of interface, the integration of intelligent design knowledge-base (IIKB), graphical format of output, flexibility in use and navigation, significant thermal performance analysis etc.

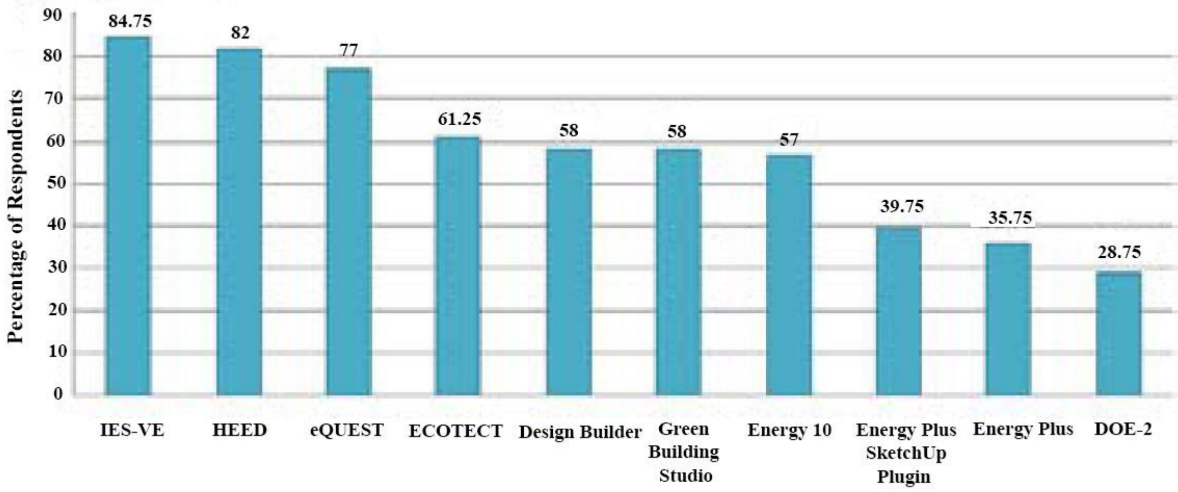


Figure 9. Criteria ranking of 'Architect Friendly' tools [63].

IES-VE is Building Information Modelling (BIM) software which has been developed for building energy simulation applications. IES-VE is a 3D modelling simulator that can be used for HVAC simulations, lighting calculations, thermal analysis, surface solar radiation, and CO_2 emission measurements. This software can interact with other 3D CAD software to import the drawings from them. Specially, IES-VE developed a Revit plug-in Toolbar which provides the ability to develop BIM analysis inside the Revit software. By using IES-VE, different materials, site location, glazing properties and weather conditions can be assigned to a specific case study. IES-VE connects the climatic conditions to model results and generates detailed reports for both. IES-VE provides distinct modules that can be used on various investigation case studies. In addition, IES-VE is comprehensive software frequently used for environmental parametric analysis [64]. Parametric analysis tests the performance of a building through progressive modifications of specific design elements. Some of the most important modules of IES-VE software can be considered as follow:

- SunCast module: to study solar gain in conjunction with solar control devices,
- Radiance module: to study the daylight illuminance,
- ApacheSim module: to develop a dynamic simulation for creating energy reports.

To demonstrate the application of the IES-VE software for building simulation, different case studies from literature are presented here. Hammad and Abu-Hijleh explored the influence of external dynamic louvers on the south, east and west oriented facades on the energy consumption in an office building located in Abu Dhabi, UAE. They used IES-VE software to predict the energy performance of the overall office module due to external louvers. They compared dynamic facades to another simpler method of using light-thermometer controlled light dimmers. The results indicate that only 24.4%, 24.45% and 25.19% for potential energy savings for light dimming strategy on the south, east and west oriented facades, respectively. However, the proposed dynamic louver system with light dimming strategy resulted in 34.02% for the south, 28.57% for the east and 30.31% for the west orientations. They did not validate the software results with any experimental data as they specifically mention that this commercial software (IES-VE) was chosen mainly due to its accuracy, versatility and user-friendliness [65].

Pollock et al. [66] focused their research on the current IES office building as an example of how to evaluate the impact of a variety of envelop thermal characteristics and low carbon technologies on the energy performance of the building. IES-VE was used to conduct a series of sensitivity analyses on a set of design parameters such as building orientation, construction, and natural ventilation scheme integrated with window type and opening area, shading devices and how they are positioned, daylighting, heating strategy. It has been shown that both daylighting levels and energy performance can be improved upon without compromising on thermal comfort.

Moghimi et al. [67] used IES-VE software to find the effectiveness of radiant barrier insulation in a typical large scale hospital selected as a case study in Malaysia. They considered hospitals with 24 hour operation as a large energy consumer. In the hospital, 62% of total energy consumption is for air conditioning. Their study compared air conditioning energy consumption of the hospital with and without building insulation. The results for insulated roof showed a reduction in annual cooling energy for the rooms under the roof about 5.15%, equal to 173.5 MWh/yr. They compared the modelled energy consumption results with three years of electricity bills to validate the software performance. Cooling energy saving in the hospital, annual saving cost and CO_2 emission reduction, via applying reflective insulation were calculated with IES-VE software. The results outlined 173.498 MWh annual energy saving, USD$17,350/yr and 85 tons reduction of CO_2 from the environment.

Almhafdy et al. [64] used empirical evidence for identification of the aspect ratio of a courtyard and its orientation as two design variants which are critical to the microclimatic performance of courtyards. They considered the U-shape courtyard in a general hospital in Malaysia (Figure 11). The aim of their research was to verify two critical design variants affecting the performance of an institutional scale courtyard in a tropical climate. They combined experimental and simulation methods in their study. In the field study air temperature, humidity and wind patterns were recorded. The simulation study was performed using IES-VE in two parts beginning with a calibration procedure, followed by the parametric analysis. The process of their research is shown in Figure 10. A continuous measurement was taken inside the U-shape courtyard during working hours. The data were later exported to Microsoft excel for analyses. A calibration procedure by comparing the simulation results with the field measurements was performed prior to parametric analysis. They followed similar procedures conducted by Leng et al.[68] using only the air temperature parameter for calibration.

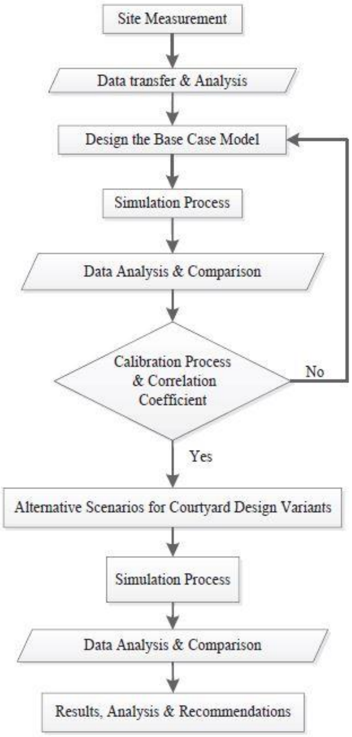


Figure 10. The overall methods of Almhafdy et al's paper [64].

In the parametric analysis of courtyard design the variants are aspect ratio and orientation. Regarding the aspect ratio, they considered courtyard height changing from 4m to 24m which represents a single-storey and high six-storey building, respectively. Also, they investigated four cardinal directions namely north, south, east and west for analysing the orientation parameter.

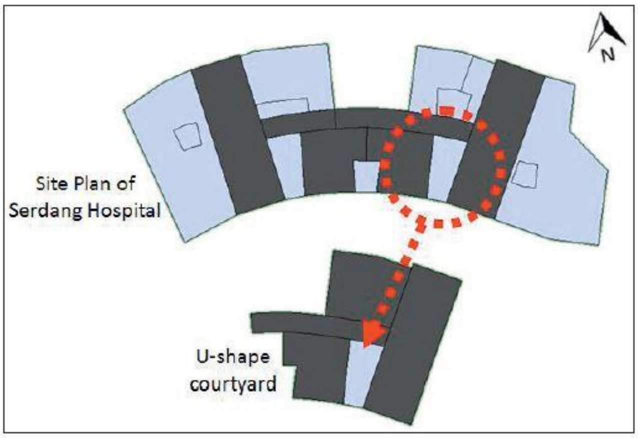


Figure 11. The U-shape courtyard site plan in Serdang hospital in Malaysia [64].

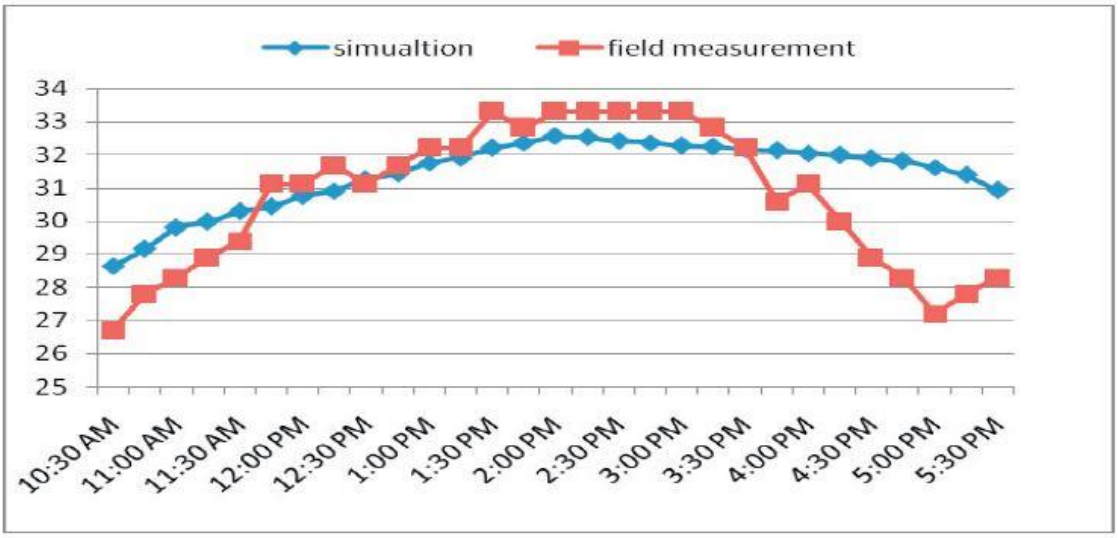


Figure 12. Calibration the base case model with the data recorded on site [64].

After calibration of the base case model of U-shape courtyard and field measurement readings, the correlation coefficient was found to be about 93% in terms of air temperature which shows a good match between the field measurements and the simulation outcome (Figure 12). Thus, the results have proved the validity and reliability of IES-VE as a tool for analysis. The final evaluation indicates that the effect orientation as observed from the recorded air temperature data shows that the effect was less but still significant. Also, the increment of height of courtyard enclosure reduces air temperature inside the courtyard as well as the rooms located at the peripheral of courtyard.

There is very limited number of documents in the available literature about building simulations with IES-VE software in different applications. Moreover, this software is relatively new and rarely was used for cool roof application. As briefly discussed, in the available documents for IES-VE, this software showed a good performance for different building simulations.

2.7 SUMMARY

This chapter has presented the analysis of the most relevant literature and identified the gaps worthy of further research that are which will be developed in the next section. The gaps are:

- No academic research has been carried out to evaluate the potential of cool roof application in different climate zones of Australia and no peer reviewed paper has been published.

- IES-VE software package does not appear to have been used for energy analyses of cool roof applications previously.
- The extent of potential benefit of applying cool roof on this particular type of building (one-storey large commercial building in different climate zones of Australia has not been quantified and reported in the literature.

This study intends to fill the gaps with the coming methodology in the next chapter.

Chapter 3: Methodology

3.1 RESEARCH PLAN

This study investigates the energy savings, the temperature reduction inside the building and CO_2 emission reduction, achieved by replacing an existing commercial building's flat roof with a more reflective 'cool roof' surface material in different climate zones of Australia. The case study is a single-storey retail store located in Brisbane's southern suburbs in Logan City. IES-VE software is used for developing the model of the case study building. The IES-VE software was chosen due to its accuracy and validity which has been confirmed in literature as well as the availability of the software for this study.

To obtain expertise in using IES-VE software, different tutorials were completed prior to developing the model for cool roof studies. Then, the basic model of the case study was developed with respect to construction plan and building information. Precise data for building specifications such as geometry, construction material, solar reflectance, occupant behaviour were loaded into the software to develop an accurate model. This information for the case study either was available or was assumed based on different scientific resources. Furthermore, an appropriate Australian weather file was imported into the software to run the simulation and obtain the initial simulation results (see page54).

After completing the basic model and generating the initial simulation results, the validation phase was initiated. The actual data (collected from field study) including temperature at different locations in the building and energy consumption from the air conditioning plant were available for 'before' and 'after' cool roof coating. This data was used to validate the model. The simulation was run several times and the obtained results compared to actual data in an iterative validation process. Depending on the difference between the actual and simulated results, a few actions were considered to improve the model. This process was continued until achieving a high level of accuracy which is the validated model.

The cool roof technology effect on the annual energy saving and temperature reduction for the validated model of the case study (a building in Arndale shopping centre) were analysed in IES-VE software. The simulations were run for different infiltration rates for further analyses of the cool roof technology effect on temperature and energy consumption reduction for the case study.

Extrapolation of the results for other climate zones was then performed. This was undertaken by changing the weather data input file in the IES-VE validated model and calculating the amount of annual energy savings resulting from cool roof application in the different climate zones of Australia. The simulations were run for seven different climate zones and the amounts of annual energy saving obtained. Therefore, relevant information for this building typology (large single-storey commercial building) was achieved to contribute to develop a guideline for cool roof application and to identify the zones with higher priorities of cool roof application throughout Australia.

In summary this project consists of five interlinked modules:

Module 1: Developing a base model in IES-VE for the case study retail store (a building in the Arndale shopping centre) which includes: Selecting or importing an appropriate weather file; Using the construction plan and other sources of information to input building geometry into the software; Modelling building information such as construction material, humidity, infiltration rate, and residence behaviour based on available or assumed information.

Module 2: Running the simulation to obtain the initial results for temperature reduction and energy consumption.

Module 3: Validation of the IES-VE model by comparing the simulation results and actual data for before and after cool roof coating.

Module 4: Analysing the effect of cool roof technology on energy saving and temperature reduction for the case study with the validated model in the IES-VE software.

Module 5: Generalizing the results of the developed cool roof model to similar types of commercial buildings in the different climates of Australia.

3.2 CONCEPT MAP

The methodology has been presented in the following picture Figure 13:

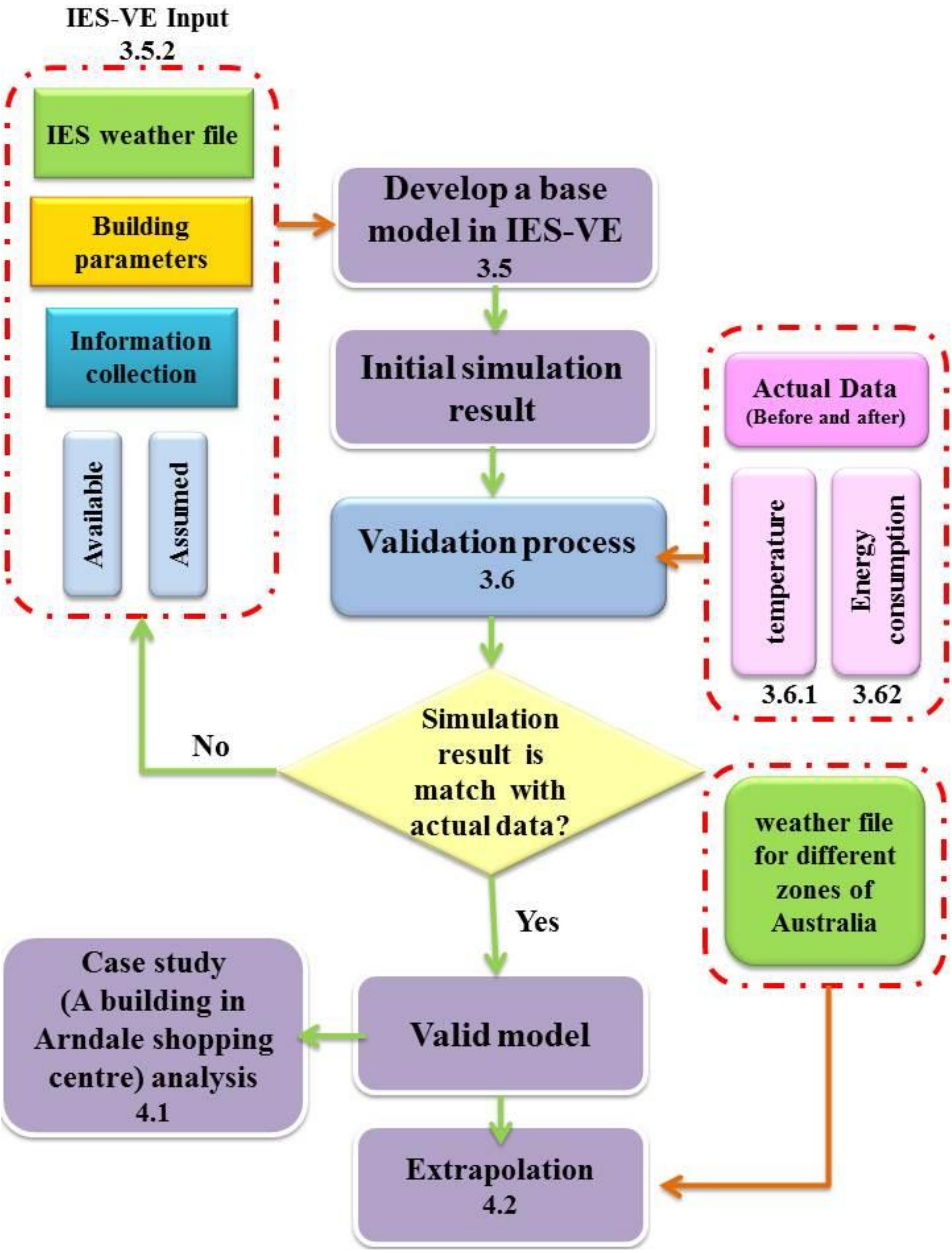


Figure 13. Research methodology concept map (numbers in each box refer to the section of the thesis).

3.3 CASE STUDY

An air-conditioned retail building in Brisbane's southern suburbs was selected as the case study building. An aerial view of this shopping centre and selected building as a case study is presented in Figure 14.

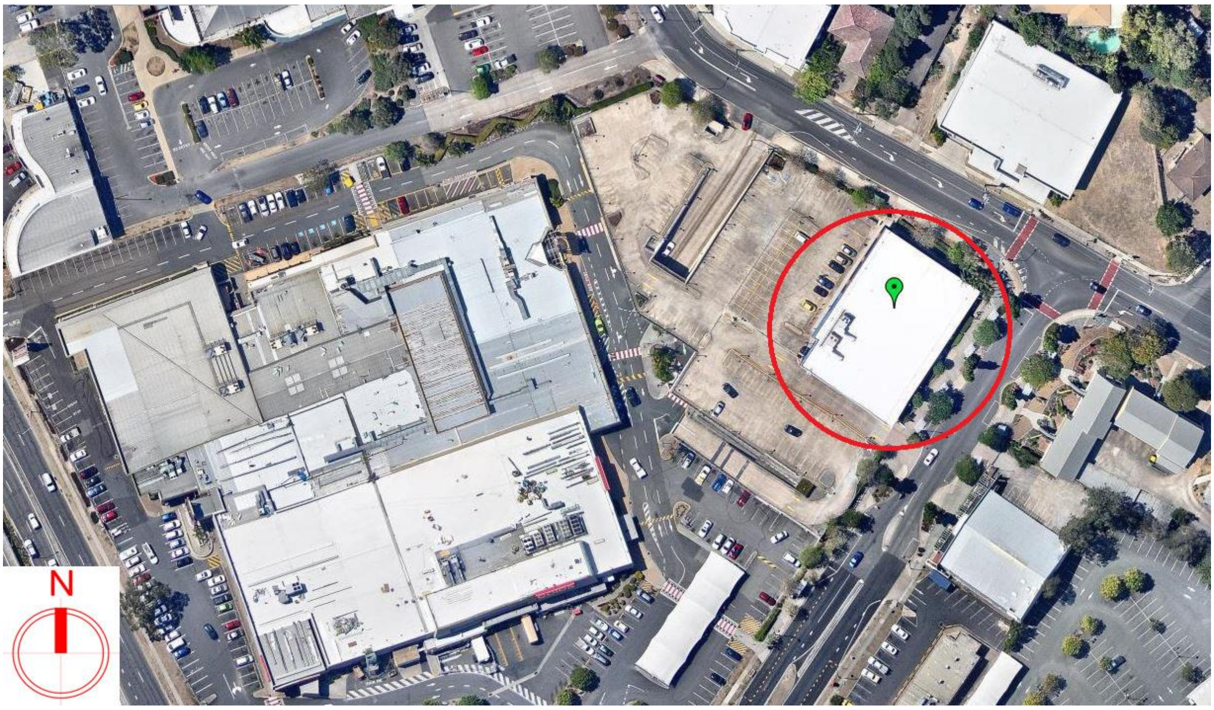


Figure 14. Arndale shopping centre aerial view and selected case study (Jun 2014; image from nearmap.com).

This case study building is a large single-storey retail building with a fairly flat roof in the Arndale shopping centre. Based on its design style and construction, it appears that the building was constructed in the 1990s. This building has two tenancies (a clothing store and an appliance store), with some storage and bathroom facilities. Each store has a small storage area which is separated from the main shop floor by internal partitions. The two tenancies are completely separated by a full height firewall. The building material is concrete panels but mostly steel and (dark blue) and glass. This building has insulation in its roof only (directly below the roof sheeting); there is no insulation on the suspended ceiling. The roof is grey colour. Both of the shops are air-conditioned via roof-top mounted air-conditioning unit. The case study opening hours are 9:00 to 18:00 every day. Figure 15 shows four pictures of the retail store taken from different directions.

(A)

(B)

(C)

(D)

Figure 15. Elevations: (A).North West - (B).North East - (C).South East - (D).South West.

3.4 COOL ROOF APPLICATION FIELD STUDY

The field study [69], carried out for a different research project, was performed in two phases which were 'before' and 'after' cool roof application. For data acquisition, the building was continuously monitored every half an hour by the researchers for approximately one year, as shown in Table 2.

Table 2. Timeframe of the field study.

	Field study duration	Date
1	Before cool roof application	31/08/2013-18/11/2013
2	Cool roof coating performance	18/11/2013-21/11/2013
3	After cool roof application(end)	21/11/2013-06/08/2014

Figure 16 and Figure 17 are pictures of the roof surface before and after applying cool roof coating on the shopping centre.

Figure 16. Roof surface before cool roof coating.

Figure 17. Roof Surface after cool roof coating.

The cool roof material which was used in this project is THERMOBOND HRC, Heat Reflective Coating, from SHIELDCOAT PTY LTD. The characteristics of this material are shown in Table 3.

Table 3. Cool Coating Material Characteristics [70].

Material ID	**Result, Air Mass=1.5**	**Avg.**
Thermobond HRC White 1	Solar Reflectance	0.875
	Emittance	0.89

A number of thermometers collecting the temperatures were installed in different parts of the building and its roof. The temperature data was collected from indoor and outdoor, the top and underneath surfaces of the roofing, the ceiling surface and the ceiling void. Figure18 is a schematic section across the width of building to show the placement of thermometers inside and outside the shopping centre which have recorded the variables every half an hour during the period of data collection.

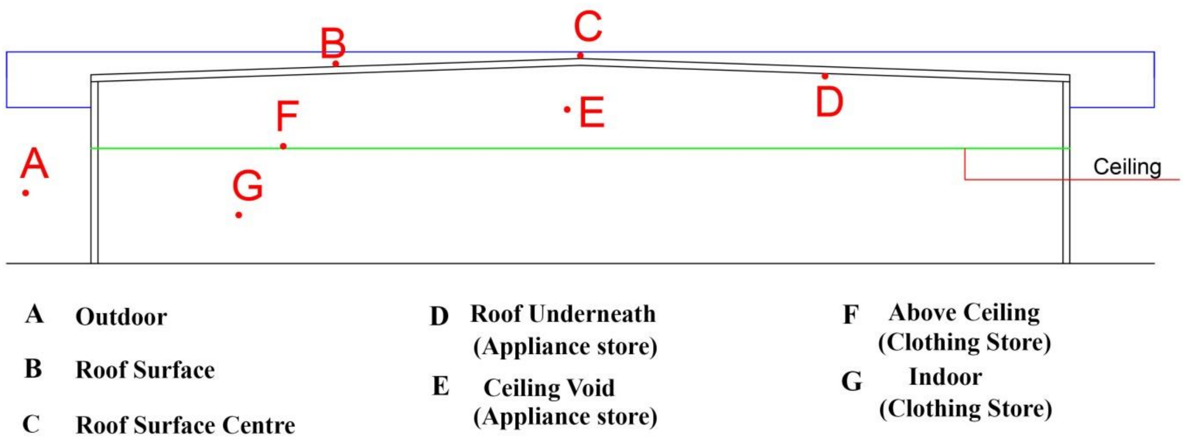


Figure18. Locations of thermometers in the case study building.

Thermometer (A) was positioned outside near the building to gain site specific temperature measurements and (G) thermometer was installed to record the indoor temperature during the field study. Due to some problems during the project, such as tenant's behaviour and broken thermometers, (A) and (G) measurements were removed from the field study. There is no data available for these thermometers. Since the data for (A) thermometer is not available, data from a Bureau of Meteorology (BOM) was used for actual weather file. From the available thermometers, (B) and (C) were collecting external surface temperatures. Since the building is going to be modelled by IES-VE software and this software shows only the internal surface temperatures, the temperature for these two thermometers would not be available in the simulation results. Among the three remaining thermometers, (E) and (D) were in the appliance store and thermometer (F) was in the clothing store. The IES model can show the temperature for each of these places. Also, an energy meter was installed to record the energy use (kWh) of the building air conditioners every half an hour to supplement the other data.

3.5 DEVELOPING THE IES-VE MODEL FOR THE CASE STUDY

For developing a model in the IES-VE software, the geometry of the building was required for drawing the 3D model of the building in the software. Then, the input files including building parameters and weather data were imported into the software and make the model ready for running the simulations. Due to the lack of documented information, appropriate assumptions and number of site visits in order to find the more accurate information were performed for developing the model which will be discussed in this section.

3.5.1 Construction material and plans

The case study building was erected in the 1990s. Unfortunately, no construction plans or building material specifications were available. Architectural plans were developed based on site visit which included visual inspection and measurement of key dimensions. Some information about the construction material, the tenants' behaviour, infiltration and leakage of the building were also assessed during the site visits. Figure 19- Figure 25 show the plans that were created in AutoCAD as a result of the site visits. All dimensions are in metres.

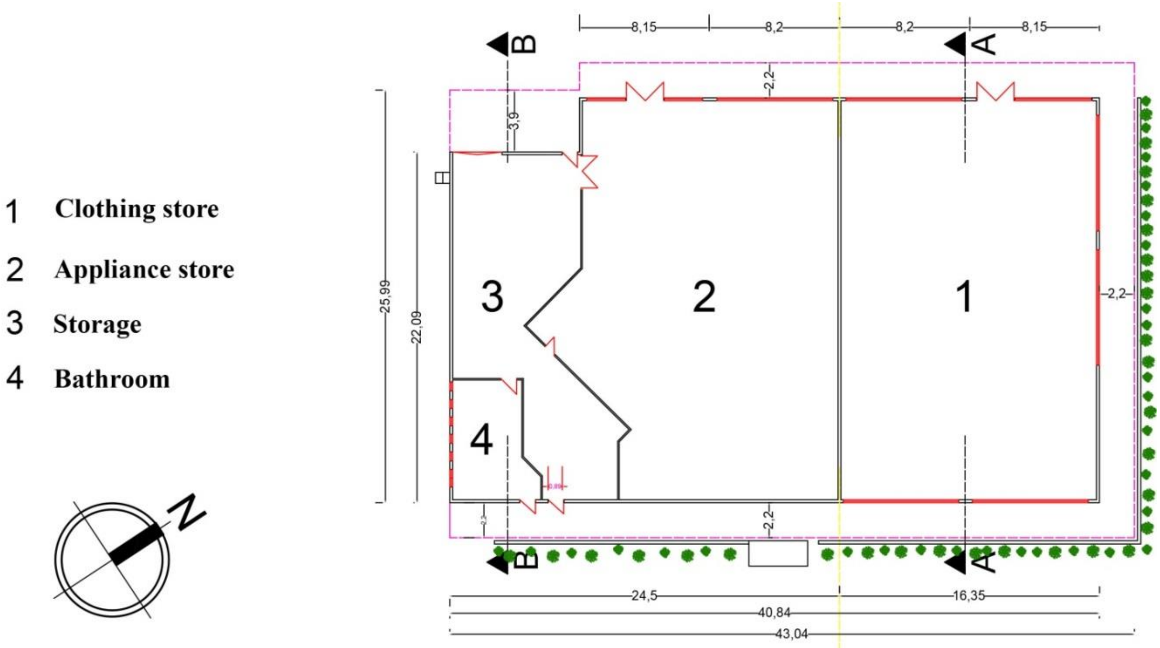


Figure 19. Architectural Plan.

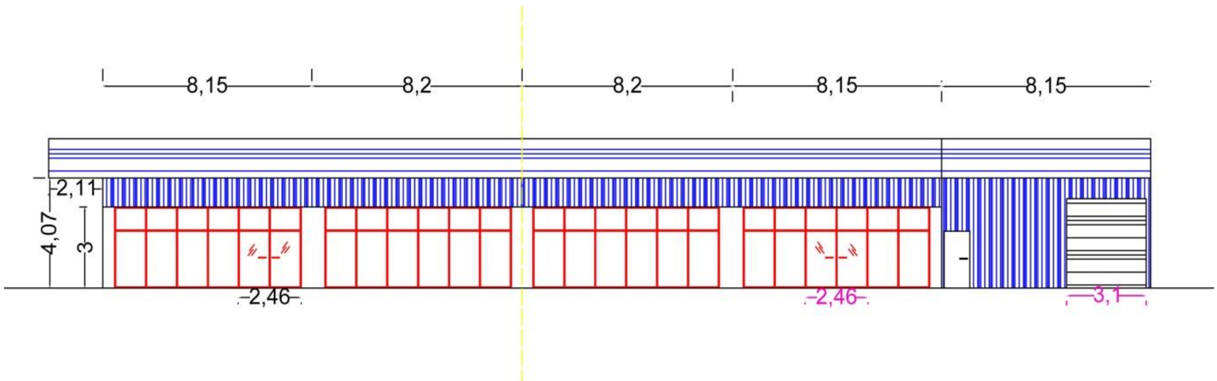


Figure 20. North West Elevation.

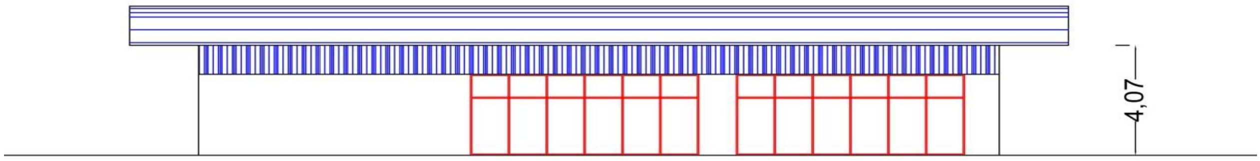


Figure 21. North East Elevation.

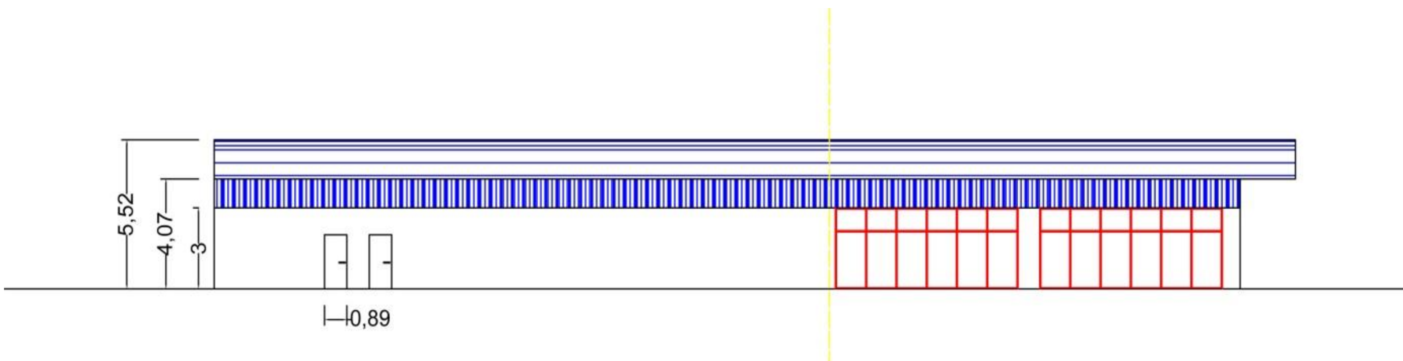


Figure 22. South East Elevation.

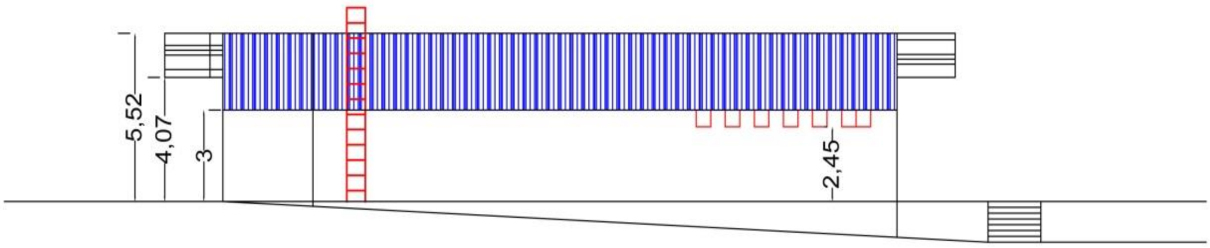


Figure 23. South West Elevation.

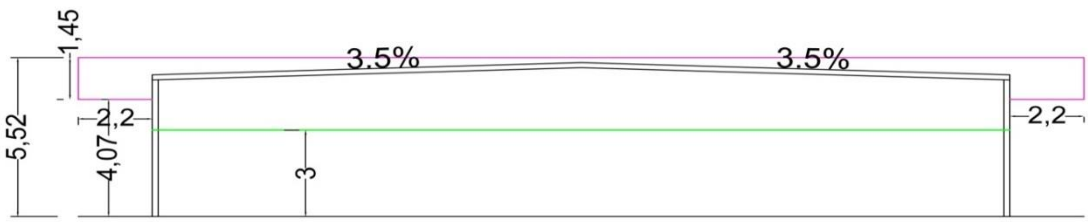


Figure 24. Section A-A.

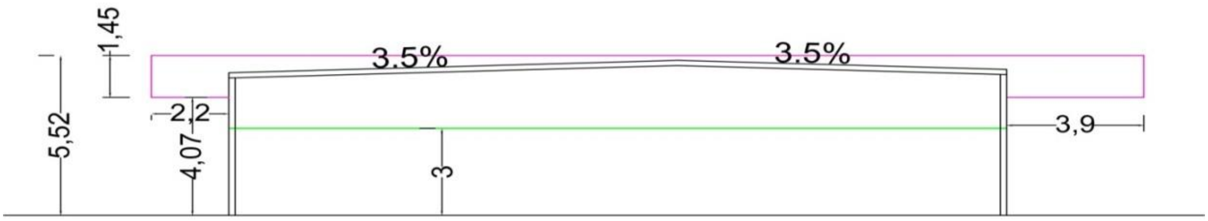


Figure 25. Section B-B.

3.5.2 IES-VE input files

Two input files are required to run the simulation in IES-VE software: building parameters input and weather data input file.

Building parameters input

First, the building geometry was developed inside the IES-VE software. Four distinctive areas (room1-4) were defined in software: the clothing store (room 1), the appliance store (room 2), a moderate sized storage room (room 3) and the bathroom (room 4). The small spaces in each shop were not taken into consideration for the sake of modelling simplicity in IES-VE.

The simulation software required precise characteristics of material input such as R-value, absorptance, emittance etc. Building parameters input file was defined based on available or assumed information to develop a model. A visual inspection of the site was conducted to confirm main, visible construction elements to identify the type of material and construction characteristics. Since no construction drawings and documents for the building were provided, the first step relied upon information expressed in the Building Code of Australia (BCA) for classification of commercial buildings for Brisbane which is in climate zone 2 (see Table 4). This information was used to identify likely R and U-values in construction materials at the time. These characteristics were changed during the simulation to reach more acceptable values for R, U, surface absorptance and emittance of construction material based on comparison between simulation and actual data. This process is the model set-up against actual data from the field study to obtain more accurate construction material characteristics.

Table 4. BCA- minimum R-values for climate zone 2 - class 6 (commercial buildings) the initial assumptions for R-values [71].

Building elements	$\mathbf{R_T}$ (m^2K/W)
Commercial roofs	3.2 (light coloured roof, solar absorptance ≤0.4)
Commercial walls	3.3
Commercial floors	2

Two separated air-conditioning systems were mounted on the roof for clothing and appliance stores. HVAC modelling was not carried out in this project and a fix set-point was defined to run the air-conditioning system in simulations. The air-conditioner of appliance store in model was chosen to be continuously off and no internal gains were considered for this shop since the appliance store was vacated a few days after the start of the field study. Although, for clothing store all internal gains such as the number of people, the type and number of lights and the facilities inside the shop was imported into the software. Furthermore, the appropriate values of humidity and infiltration rates were defined for the model.

Weather data input

The available weather file for Brisbane in the IES-VE software is Brisbane Airport, for years prior to 2002. The case study is located in Logan City close to 35 Km away from the Brisbane Airport. Figure 26 illustrates the distance between Logan City, Brisbane Airport weather station and Arndale shopping centre. Using the Brisbane Airport weather file rather than Logan City actual weather file, may result in some uncontrolled errors between simulation results and actual data. In primary simulations with old version Brisbane Airport weather file, critical differences between the simulation results and the actual data were observed. To solve this issue, generating a custom weather file for 2013 (the field study timeframe) was considered initially. However, due to the lack of available data this idea was not possible to perform (see Appendix A). Therefore, the BOM recorded actual weather data file for the 2013 calendar year was made available, in suitable IES format, for Brisbane City (040842 Brisbane Aero QLD) and was utilised in this study. This weather file was TMY2 file (Typical Meteorological Year 2) which are data sets of hourly values of solar radiation and meteorological elements for a 1-year period of 2013[72].

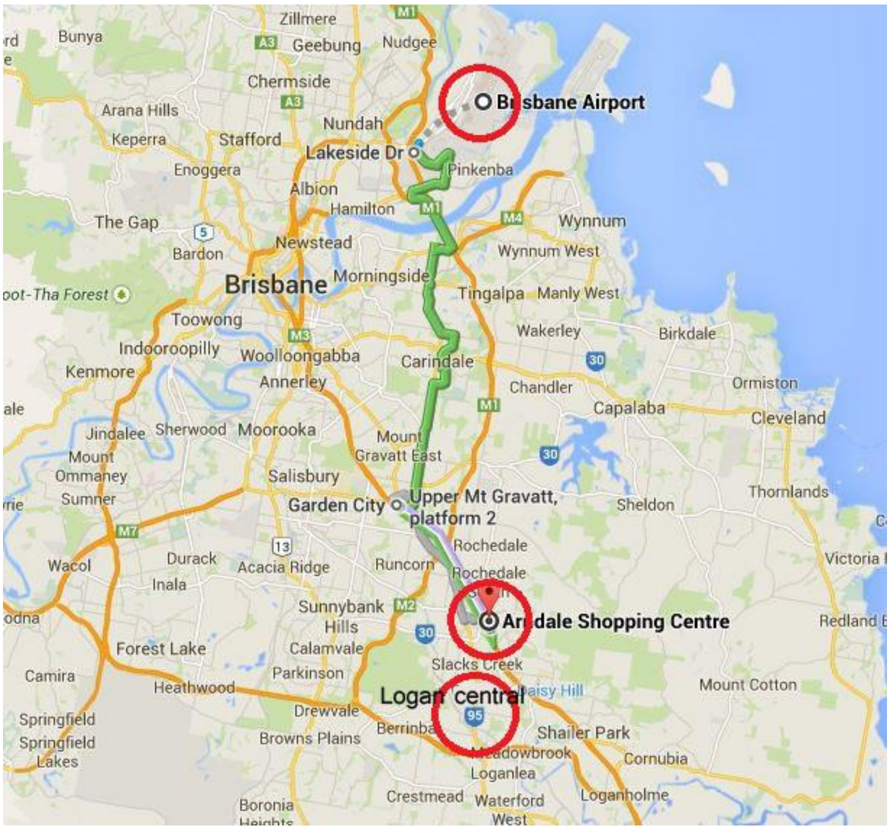


Figure 26. Distance between Logan City, Brisbane Airport weather station and Arndale shopping centre (Aug 2014; image from https://maps.google.com.au).

3.5.3 Source of error/Uncertainty in the building

There are some building factors which remained unknown until the end of the project. Also, in the building sector, there are some factors which are not able to be modelled and thus needed to be estimated, such as the number of people and the time they are utilizing the stores, people's behaviour, the number of times and the periods that the doors are opened and the manual changing of air-conditioning settings. A few days after the start of the field study, the appliance store was vacated. During the observation of the building, some assumptions about these factors were considered for use in the simulation software. The site visit proved that the door of the clothing store was left open sporadically. When asked the reasons for that behaviour, the staff answered that it was a way to show that the shop was open for business. Some days in Brisbane are hot and they prefer to close the door to keep the inside cooler. They do not follow this procedure all the time which may result in predictable and inevitable differences between simulation results and real data (discussion about infiltration rates in section 3.6.2).

3.6 VALIDATION

The model was validated with respect to actual data prior the simulation results being used to perform any analysis. Actual data was divided in two categories: temperature and energy consumption. Validating the model with both of these parameters leads to a model which can be used for energy and temperature simulation analyses. In this section, the model set-up process by finding the appropriate values of material properties and operational parameters is discussed. This process can be summarised as follow:

- Temperatures modelled by IES was compared with measured temperatures before cool roof coating for determining the material properties such as R and U-values, surface absorptance, emittance and ceiling void infiltration rate, because these parameters have the greater influence on temperature.
- Energy modelled by IES compared to actual monthly energy use to determine the operational parameters such as infiltration rate, air-conditioner unit characteristics and the humidity rate in the building which have the greater impact on energy consumption simulation results.
- By applying any changes in material properties or operational parameters, energy consumption and temperatures obtained from simulation results were checked with actual data and the corresponding errors were calculated. This process continued until reducing all errors below the acceptable range.
- After completing this set-up process, the model was run for a number of days without any changes in any parameters and validity of model was confirmed.

Based on all information that was available or assumed about the building, a model of the case study was developed in IES-VE. Temperatures from different thermometers located inside the building were compared to the surface temperatures given by the IES-VE program in the same locations and energy consumption predicted in IES-VE were compared with actual energy use per month during the field study. Based on the result of these comparisons, alterations were made to the IES-VE software to align the two source temperatures and energy consumption more accurately. It is important that only one factor changes at a time to understand the effect of that particular factor in the simulated result. Following this step by step process, a valid model representing the actual building was achieved. The difference between final model results and actual data should be within the acceptable range. The agreement of 5-15% error between simulated and measured quantities was expressed in the literature depending on the accuracy of measurement and simulation [48, 62, 73, 74]. The maximum error in all simulation results was reduced below the acceptable range during this study. This range has been adopted in this study.

3.6.1 Validation by surface temperature

A comparison of the surface temperature simulation results in IES and real temperatures for thermometers (D), (E) and (F) would potentially lead to changes of material properties in the model such as building construction characteristics e.g. R-value, surface emittance and absorptance to approach to more accurately matched model.

Before addressing how the model was validated by temperature, the dry-bulb temperature in the actual weather data was compared with the final IES-VE weather data input file. This comparison is shown in Figure 27. As discussed in Section 3.5.2, the available IES-VE weather file for Brisbane is from Brisbane Airport weather station for 2013 which is about 35 km away from the case study location. On the other hand, the actual temperatures for Brisbane were taken from the Bureau of Meteorology (BOM) for the field study duration. As shown in this figure, the IES dry bulb temperature is slightly less than the actual dry bulb temperature which represents the colder year compared to the actual weather data. However, after investigation, it appears that this variation of temperatures in the actual and IES-VE weather data is not significant during the year and it is accurate enough to move forward. Furthermore, this IES weather file input is the best weather data currently.

It should be mentioned that even if the dry-bulb temperature for a particular day is matched in the IES weather file with the actual weather data, the humidity should be checked because it also contributes in energy consumption. In other words, dry bulb temperature and humidity are both the main factors in weather file input which affect the building energy use.

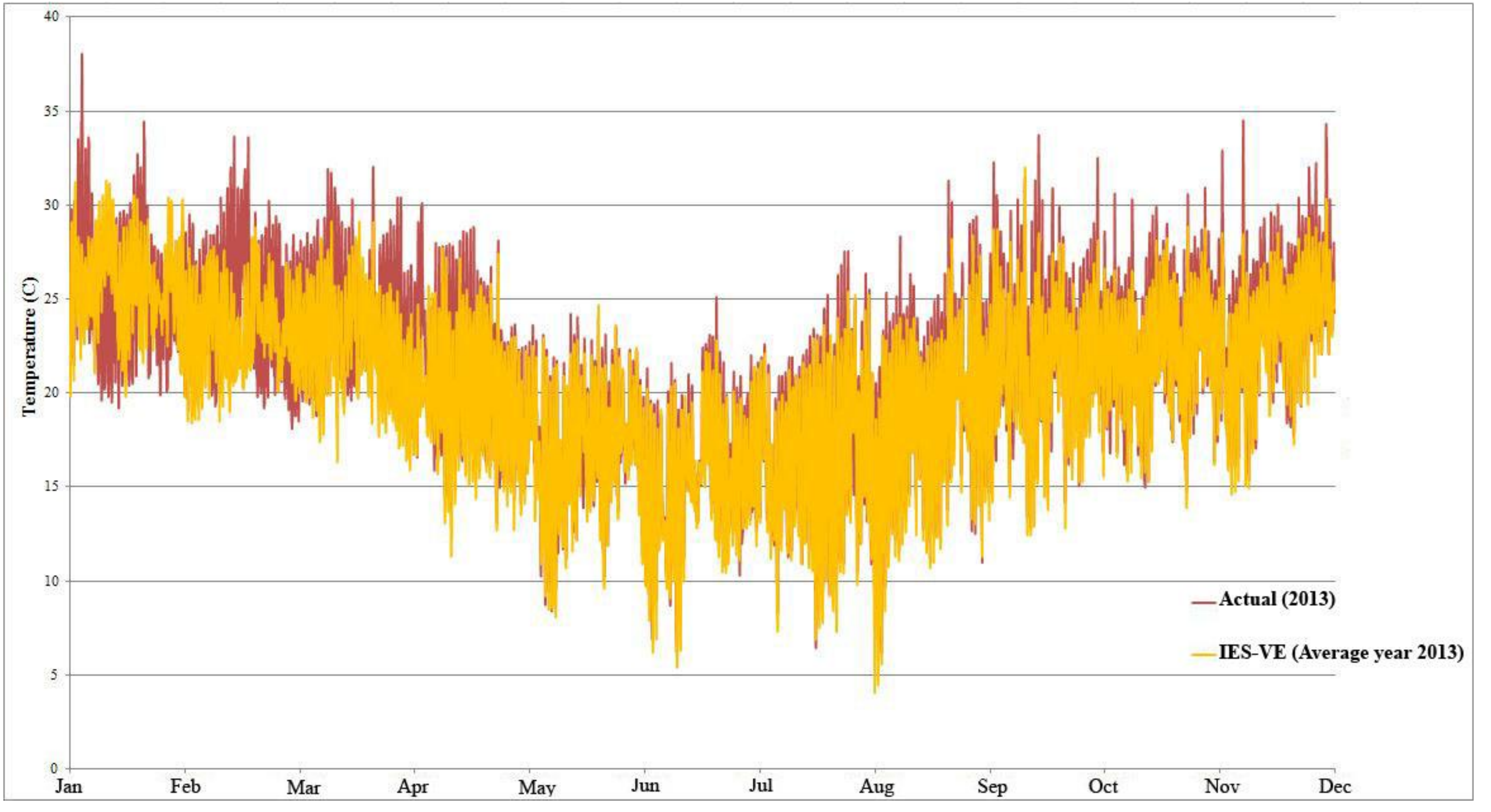


Figure 27. Comparison of dry bulb temperatures between IES-VE weather file input and actual weather data.

The 20th of October 2013 was selected as an example of before cool roof application to discuss the model set-up process in detail. First, the temperature from IES-VE and actual data was compared for this date. Figure 28 shows a difference between actual and IES temperatures. As can be seen in the graph, the IES and actual temperature both have the same trends and their temperatures vary similarly during the 24 hours of the day. In this example, the maximum of actual temperature is higher than the IES temperature by about 2 degrees whilst at other points were almost the same. As expected, in both profiles the temperature reduces during the night and increases when the sun rises and continues to increase to the highest reading about noon before graduate cooling until around 5:00. The start and end points of two trends have very similar temperatures, but the actual weather is generally hotter than the IES weather temperature during the 24 hours. The average percentage error between these two graphs is around 4% which shows a similar dry-bulb temperature in IES and the actual in Brisbane. However, it will affect the simulation results and an unavoidable difference between simulation and actual data would occur.

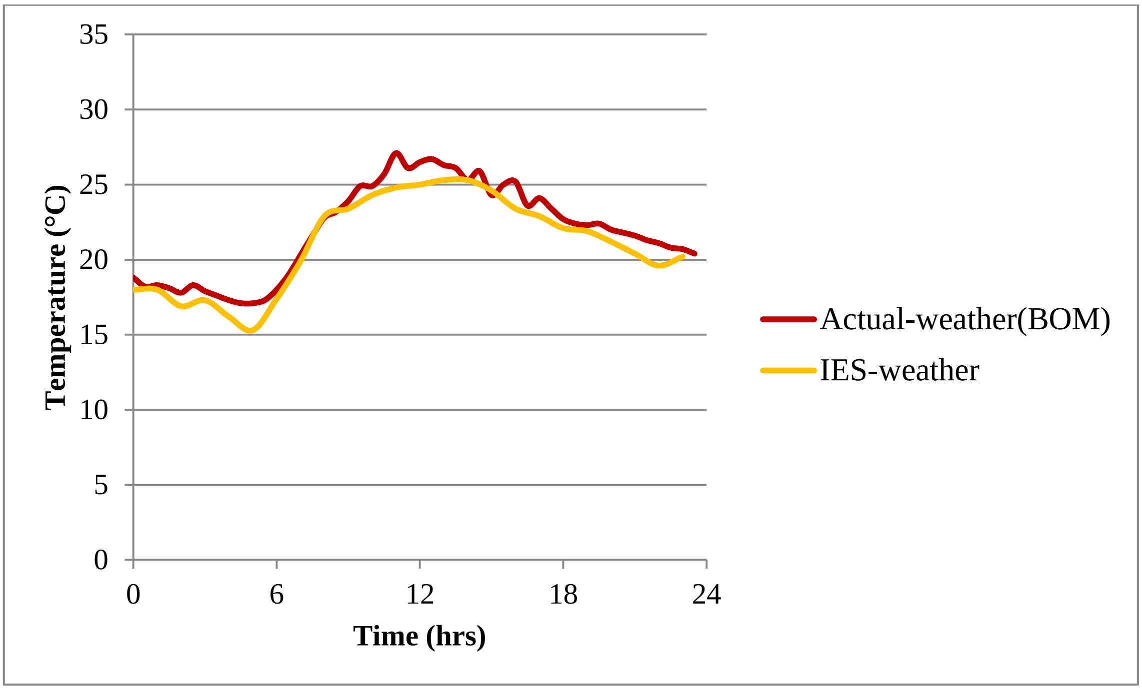


Figure 28. Comparison of Brisbane temperatures between actual and IES-VE on Oct 20th.

For verifying the temperature recorded by three different thermometers (D, E and F), the comparison between actual data before cool roof coating and IES simulation results should be performed. Regarding the difference between them, some factors were changed to obtain better simulated results. To run the initial simulations, the appropriate IES-VE weather data input file and primary values of building parameters input file were inserted into the software and the basic model was developed. Two days in each month before cool roof coating, one at the beginning and another at the end of the month, were selected to compare the IES-VE temperature simulation results with actual measured temperatures for model set-up process. Based on this comparison, the building parameters input file was modified to achieve better agreement between simulation and actual temperature results. It was found that in the building parameters input file, the material properties such as R and U-values, surface absorptance, emittance and ceiling void infiltration rate have the most influence on temperature results. Therefore, in an iterative process several combinations of those values were evaluated to achieve acceptable errors (below 15%). The model simulation results were compared to actual energy consumption data simultaneously and relevant changes made in the building parameters input file of the model in the set-up process (see 3.6.2).

To illustrate this process, a few iterations for one of the field study days (Oct 20th) before cool roof coating is shown in Figure 29. In this figure, the orange line graph is the basic result and the red one is the actual data. As can be seen, this initial result has been improved by different course of actions to achieve the acceptable range of error which is shown in purple colour.

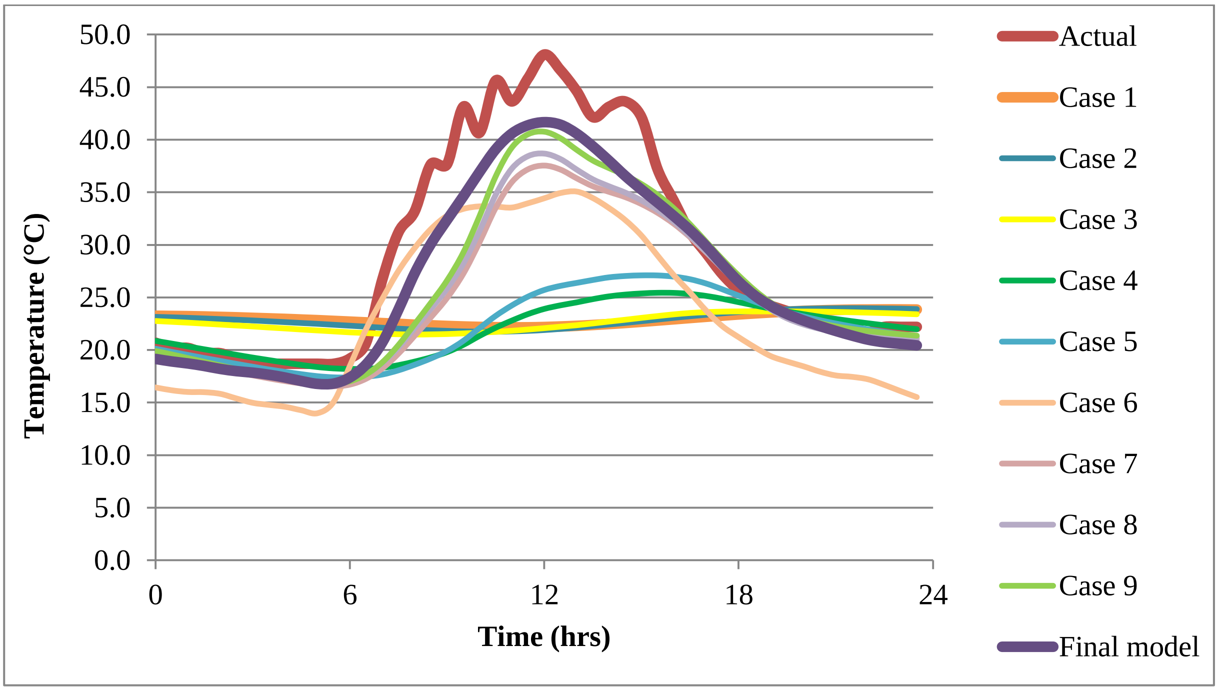


Figure 29. The Oct 20th iterative process/set-up process for thermometer D.

At first, the simulated results (shown in orange) were not found to follow the trend of the actual data (shown in red) but stayed almost steady, while the actual data varied during a day. Changing the emissivity and absorptance of the surfaces in the range of material characteristics, were found to not change the results (shown in yellow). In fact, the building model seemed very concealed and insulated from the outside weather condition. To this end, the R-value of the building envelop was reduced to make the building less thermally resistant. Therefore, the inside temperature was affected by changing the outside temperature subsequently. Finally, after some manipulation of the R-value of the building envelop, the actual and IES simulation results matched. Therefore, the real R-value of the building construction material obtained through this validation process indicates it is less than the minimum value stated in BCA. This fact shows that the range of R-value for commercial building classification which is expressed in BCA (stated previously in 3.5.2 section), was not applicable in this case study. It could be because of thermal conductivity of steel which is the main construction material or thermal bridge resulted from the poor construction in this building. Furthermore, infiltration rate for the ceiling void was increased from the default value to obtain better agreements with actual data. After lots of iterative process, the valid result (shown in purple) was obtained with the acceptable error compared to actual temperature. Table 5 indicates the modifications during the set-up process for each case.

Table 5. The Oct 20^{th} Modifications in set-up process for thermometer D on Oct 20^{th}.

Simulation results	**Modifications**
Case 1	No infiltration rate-R-value 100% BCA
Case 2	Emissivity and absorptance increased
Case 3	Emissivity and absorptance increased-R-value 90% BCA
Case 4	R-value 80% BCA
Case 5	Infiltration rate 0.25-R-value decreased
Case 6	Infiltration rate increased-R-value decreased
Case 7	Infiltration rate increased
Case 8	Infiltration rate increased
Case 9	Infiltration rate increased

The graphs below illustrate the actual and simulated temperatures from the valid model for three different thermometers (D, E, and F) positioned in different parts of the building for the selected day (Oct 20th) before cool roof coating.

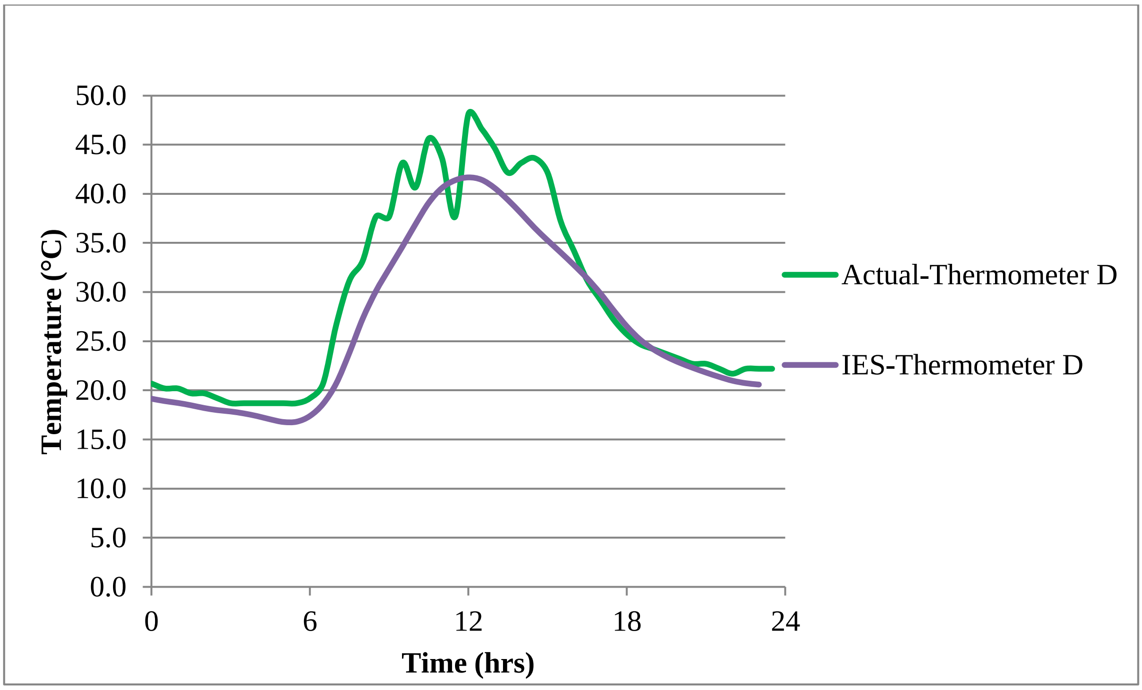


Figure 30. Comparison of D thermometer temperature between actual and IES-VE before cool coating on Oct 20th.

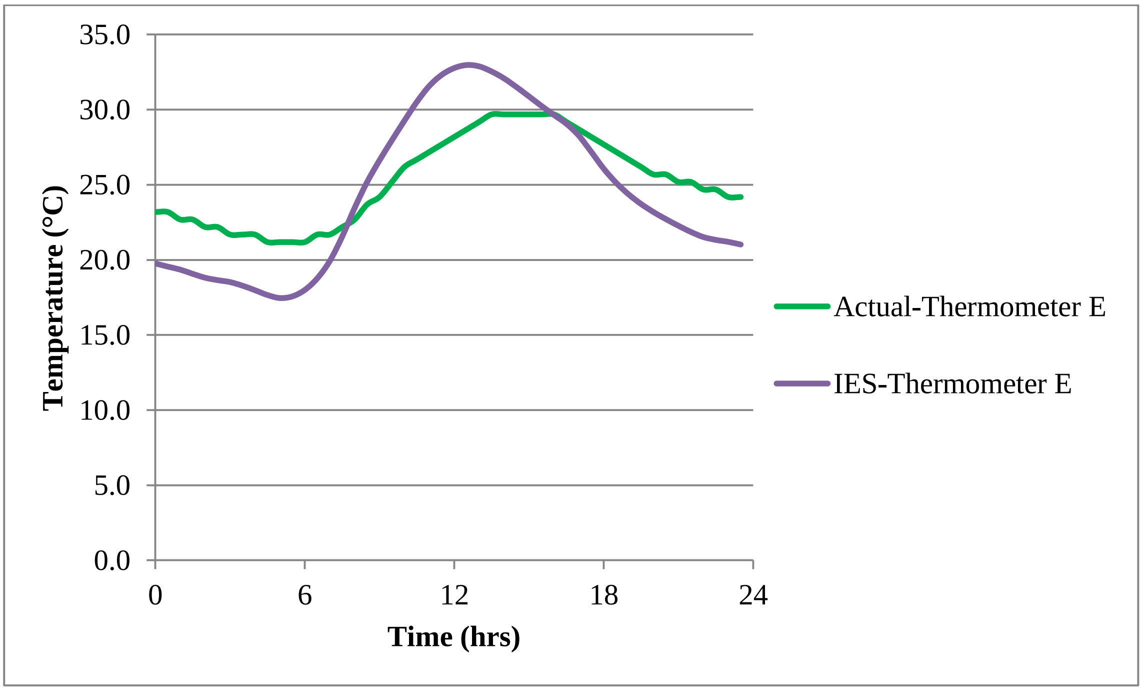


Figure 31. Comparison of E thermometer temperature between actual and IES-VE before cool coating on Oct 20th.

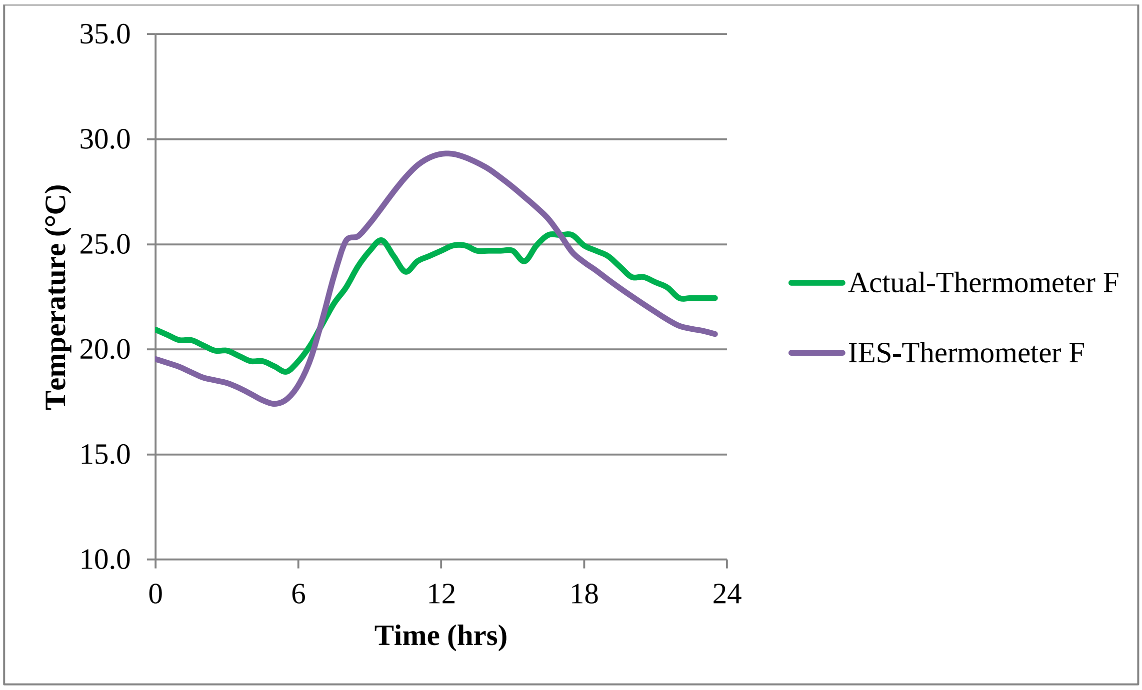


Figure 32. Comparison of F thermometer temperature between actual and IES-VE before cool coating on Oct 20th.

From Figure 30 to Figure 32, the temperatures measured before (Oct 20th) cool roof coating are seen to be similar to the IES model results after set-up process. From the last figure, it seems the lag for thermometer (F) is because the air conditioning has come on. The difference between the model and actual temperature for each thermometer calculated for this date is tabulated in Table 6. As can be seen in this table, the average percentage error between actual and simulated results for all thermometers is below acceptable range in literature (below 15%).

Table 6. Error percentage between IES and actual results of different thermometers temperature.

Thermometer	Day	D	E	F
Root Mean Squared Error (RMSE)	Oct 20th	3.64	2.95	2.33
Average percentage error	Oct 20th	12.51	11.68	10.19

The source of these errors is analysed in below in more detail. Table 7 shows the temperature difference obtained from actual and IES results for thermometer (D). The results illustrate that the temperature difference between actual and IES results is higher between 7:00-15:30. The greater difference between the actual and the IES simulation data, results in a higher average percentage error. These results trigger a comparison between the actual and IES weather data.

Table 7. The actual and IES temperature for thermometer (D) for Oct 20th.

Date	Time (hrs)	Actual-Sensor D (˚C)	IES-Sensor D (˚C)	Difference (˚C)
20-Oct	0	20.696	19.15	1.546
	0.5	20.195	18.91	1.285
	1	20.195	18.72	1.475
	1.5	19.694	18.48	1.214
	2	19.694	18.2	1.494
	2.5	19.193	17.99	1.203
	3	18.692	17.85	0.842
	3.5	18.692	17.65	1.042
	4	18.692	17.38	1.312
	4.5	18.692	17.05	1.642
	5	18.692	16.78	1.912
	5.5	18.692	16.81	1.882
	6	19.193	17.39	1.803
	6.5	20.696	18.63	2.066
	7	26.699	20.72	5.979
	7.5	31.192	23.86	7.332
	8	33.187	27.3	5.887
	8.5	37.67	30.09	7.58
	9	37.67	32.38	5.29
	9.5	43.139	34.61	8.529
	10	40.655	36.92	3.735
	10.5	45.622	39.09	6.532
	11	43.636	40.59	3.046
	11.5	37.67	41.38	-3.71
	12	48.102	41.67	6.432
	12.5	46.614	41.43	5.184
	13	44.629	40.58	4.049
	13.5	42.146	39.37	2.776
	14	43.139	38	5.139
	14.5	43.636	36.56	7.076
	15	42.146	35.26	6.886
	15.5	37.173	34.02	3.153
	16	34.184	32.74	1.444
	16.5	31.192	31.39	-0.198
	17	29.196	29.86	-0.664
	17.5	27.198	28.14	-0.942
	18	25.699	26.51	-0.811
	18.5	24.699	25.17	-0.471
	19	24.199	24.18	0.019
	19.5	23.699	23.42	0.279
	20	23.199	22.81	0.389
	20.5	22.698	22.29	0.408
	21	22.698	21.81	0.888
	21.5	22.198	21.37	0.828
	22	21.697	20.98	0.717
	22.5	22.198	20.73	1.468
	23	22.198	20.59	1.608
	23.5	22.198	20.44	1.758

Table 8 shows the actual weather data (BOM) and the IES weather input data for Oct 20th. The difference between these two weather files can be responsible for part of the difference between the (D) thermometer temperature and IES results observed in Table 7. The weather temperatures have some fluctuation around 4:00 to 14:00 which could affect the inside temperature of the retail store. However, the inside temperature fluctuations occur between 7:00-15:30 due to the thermal conductivity of the construction materials which incurs the delay of the inside temperature response.

Table 8. Actual and IES weather data for Oct 20th.

Date	Time (hrs)	Actual-weather(BOM)(°C)	IES-weather (°C)	Difference (°C)
20-Oct	0	18.8	18	0.8
	1	18.3	18	0.3
	2	17.8	16.9	0.9
	3	17.9	17.3	0.6
	4	17.3	16.2	1.1
	5	17.1	15.3	1.8
	6	18	17.4	0.6
	7	20.3	19.9	0.4
	8	22.8	22.9	-0.1
	9	23.9	23.4	0.5
	10	24.9	24.3	0.6
	11	27.1	24.8	2.3
	12	26.5	25	1.5
	13	26.3	25.3	1
	14	25.3	25.3	0
	15	24.3	24.6	-0.3
	16	25.2	23.4	1.8
	17	24.1	22.9	1.2
	18	22.7	22.1	0.6
	19	22.3	21.9	0.4
	20	22	21.2	0.8
	21	21.6	20.4	1.2
	22	21.1	19.6	1.5
	23	20.7	20.2	0.5

The thermometer (D) and (F) are verified with IES temperatures as well. Investigations showed that the reason of error for thermometer E was related to installation. This thermometer is not showing the ceiling void air temperature in actual data exactly, but in fact, was attached to the wooden material on the wooden mezzanine floor inside the ceiling void. Therefore, it was showing the surface temperature of the wooden object while the IES output indicated the air temperature inside the ceiling void. Consequently, the higher amount of error occurring between the recorded data on (E) thermometer and IES output is because they are not based on the same position; however, they both represent the ceiling void inside temperature.

It should be noted that lower error would be obtained if more thermometers were installed inside and outside the building to verify temperatures from the model with actual data. As mentioned previously, two thermometers were lost during the field study period. Loss of these thermometers reduced the accuracy and highlighted the need to implement higher data collection security during the field studies. More precise arrangements should be considered for protecting the thermometers while the case study is operating.

After completing the set-up process and achieving the valid model, the validated model was run for a number of days after cool roof coating without any changes in any parameters to confirm the validity of model. As an example, the simulation results for 20th of December 2013 are presented to show the validity of the model. For this date, the trends of the temperature data for IES and actual weather data during the 24 hours are presented in Figure 33. The IES and the actual temperature profiles are quite similar and follow the same trend. The IES temperature is higher than the actual temperature about 4 degrees at midnight. After this point the IES temperature continuously decreases until around 5:00 am while the actual temperature experiences some fluctuations during this period. Around noon when the sun is at its zenith, the IES temperature is around 1 degree higher than the actual temperature. The calculations show an average of 5% difference between the IES and the actual temperatures which can be a source of error in simulation results.

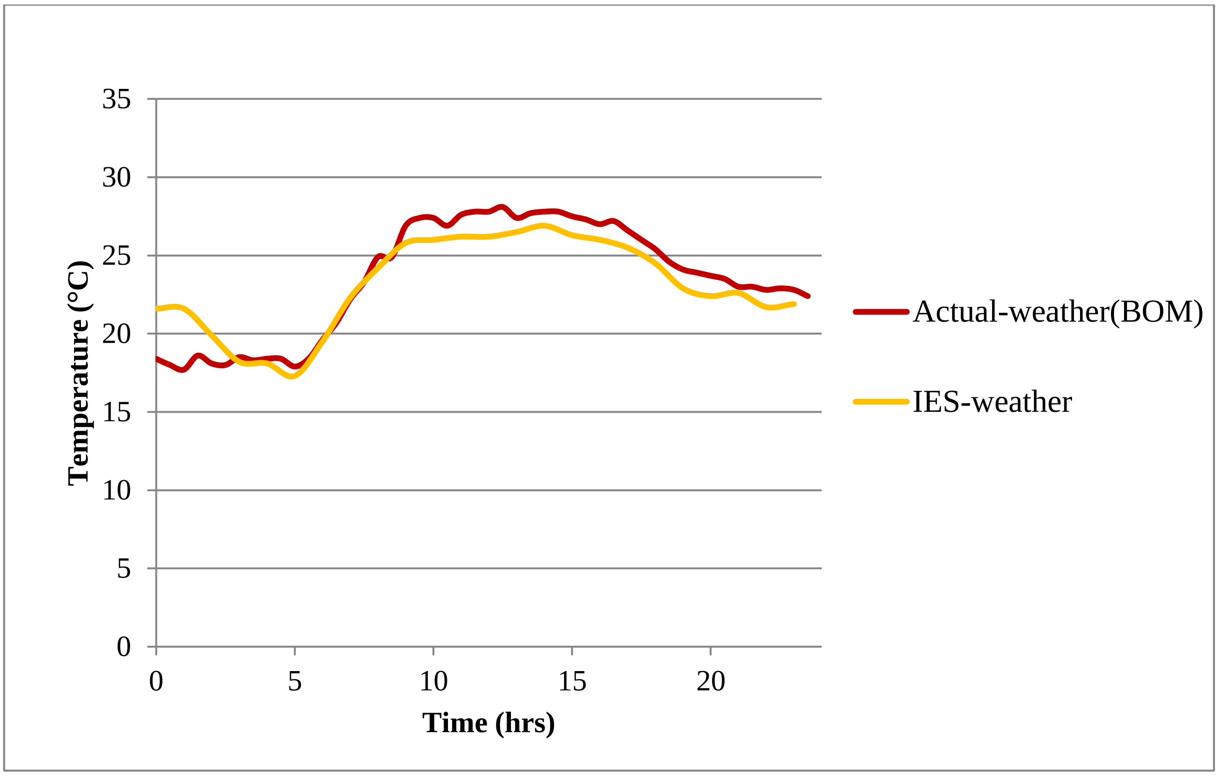


Figure 33. Comparisons of Brisbane temperatures between actual and IES-VE on Dec 20th.

As shown in Figure 34 to Figure 36, the simulation results are in good agreement with actual data for all thermometers. Root Mean Squared Error (RMSE) and average percentage error are also presented in Table 9, which confirms all values of errors are below acceptable range for validation.

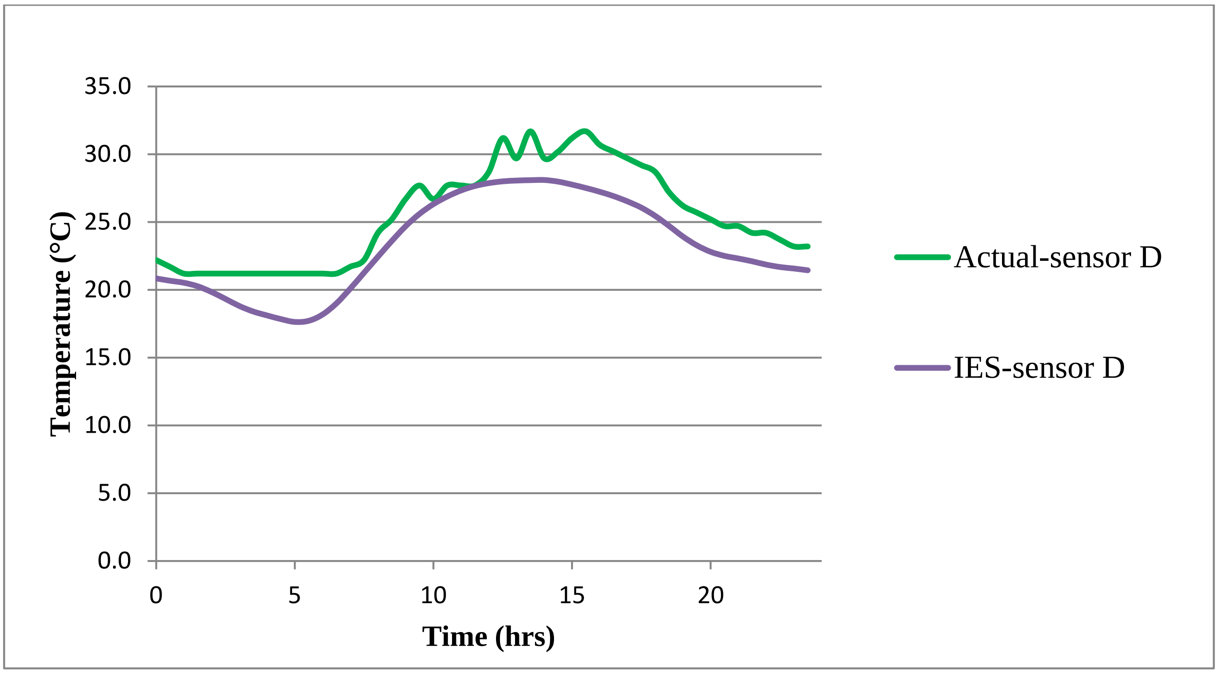


Figure 34. Comparison of D thermometer temperature between actual and IES-VE after cool coating on Dec 20th.

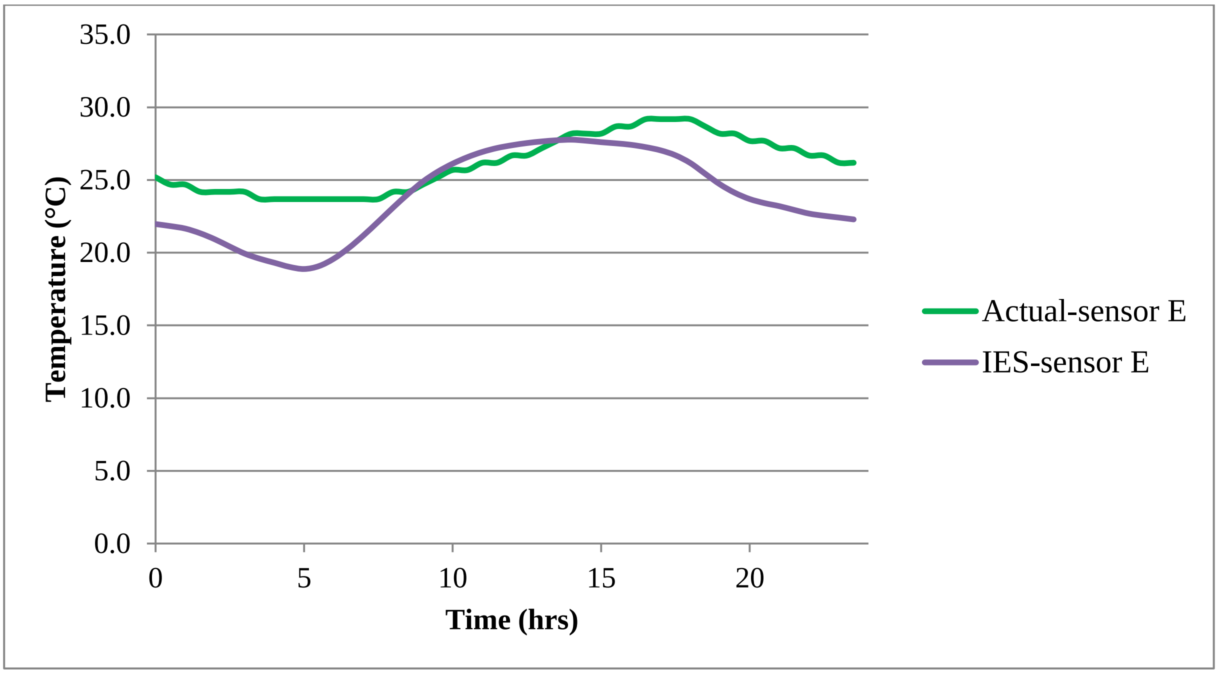


Figure 35. Comparison of E thermometer temperature between actual and IES-VE after cool coating on Dec 20th.

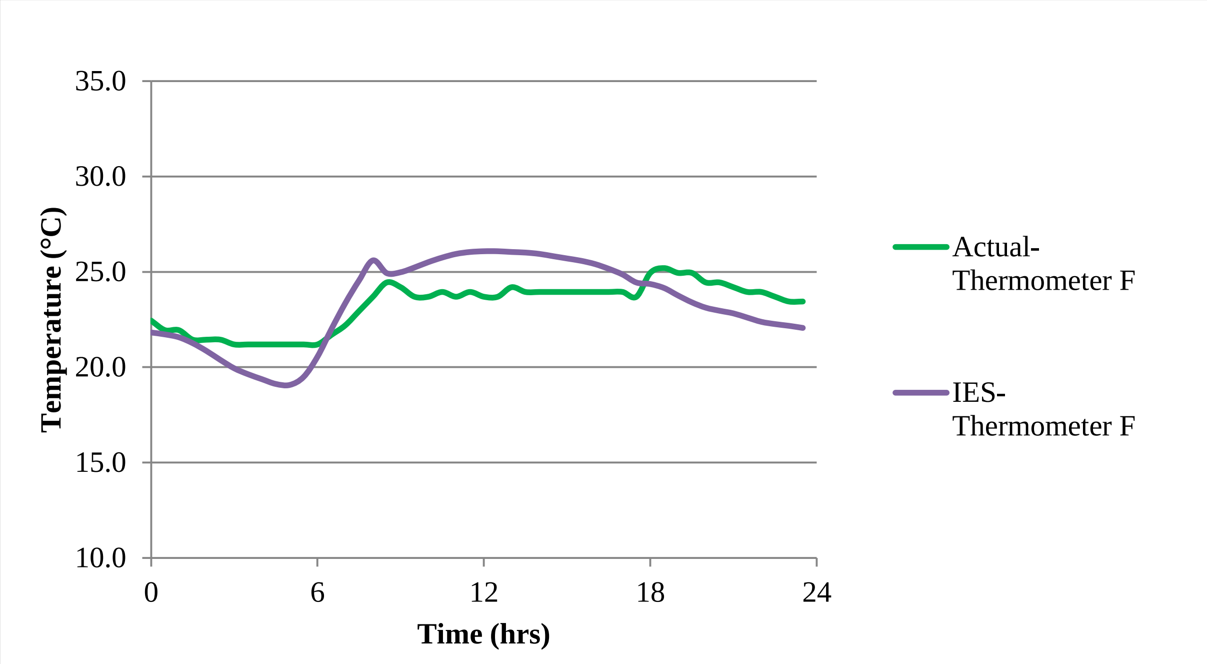


Figure 36. Comparison of F thermometer temperature between actual and IES-VE on Dec 20th.

Table 9. Error percentage between IES and actual results of different thermometers temperature.

Thermometer	**Day**	**D**	**E**	**F**
Root Mean Squared Error (RMSE)	Dec 20th	2.37	2.96	2.22
Average percentage error	Dec 20th	9.34	11.32	9.56

3.6.2 Validation by energy consumption

As mentioned before, during the set-up process the model was also verified for energy consumption performance. Any changes to match the model with actual data for temperature were checked for energy consumption as well and some relevant modifications made in the model to achieve a validated model from both a temperature and energy consumption perspectives. In the IES building parameter input file, a number of factors such as humidity, air infiltration rate and air-conditioner unit characteristics have more influence on energy set-up.

To verify the accuracy of the IES-VE model, it was manipulated several times and the result compared to the actual energy consumption data in an iterative process. A fixed value for infiltration rate (2 ACH@50 Pa) was used in the simulations at first. This value of ACH was extracted based on the case study condition from literature for Australian buildings [75-77]. The primary simulation results were significantly different from the actual records. In the IES building parameter input file a number of factors such as humidity range, air infiltration rate and air-conditioner unit characteristics were changed to achieve the acceptable error range. However, by changing the related parameters in practical range the IES-VE simulation results did not improve significantly.

After further investigation about this issue, it was found that the entrance door of the retail store was left open by tenants for a long time during working hours. The reason for this is the owner's attitude to show the shop is open during business hours. Therefore, an extra infiltration rate apart from the fixed one was added to the model for working hours duration to simulate this attitude. Then, the iterative process was performed in order to find the appropriate value for extra infiltration rate to match the IES energy use prediction with the actual monthly energy consumption. This solution improved the results significantly; however, it was found that different values for extra infiltration rate are required for each month to match the simulation results with actual data. The extra infiltration rate values are increased gradually from hot months toward colder months. There is a practical explanation for this special behavior of the model. The tenant left the door open in cold month mostly as requested by the owner but in hot month they closed the door sometimes to keep the inside cooler. This behavior is in a good agreement with the values of extra infiltration rates as the higher values of extra infiltration rates are required in cold month to match the model with actual data compared to the values in hot month. To show this set-up process, a number of iterations to find the appropriate values for the extra infiltration rate are shown in Figure 37. As can be seen, high values of extra infiltration rates were selected between 8-20 ACH@50 Pa for each month depending on tenants behaviour in using the entrance door in hot and cold days during a year. After an iterative process, it was found that the IES-VE result was matched with Actual energy use data (red colour) by a combination of different extra infiltration rates for each month (purple colour).

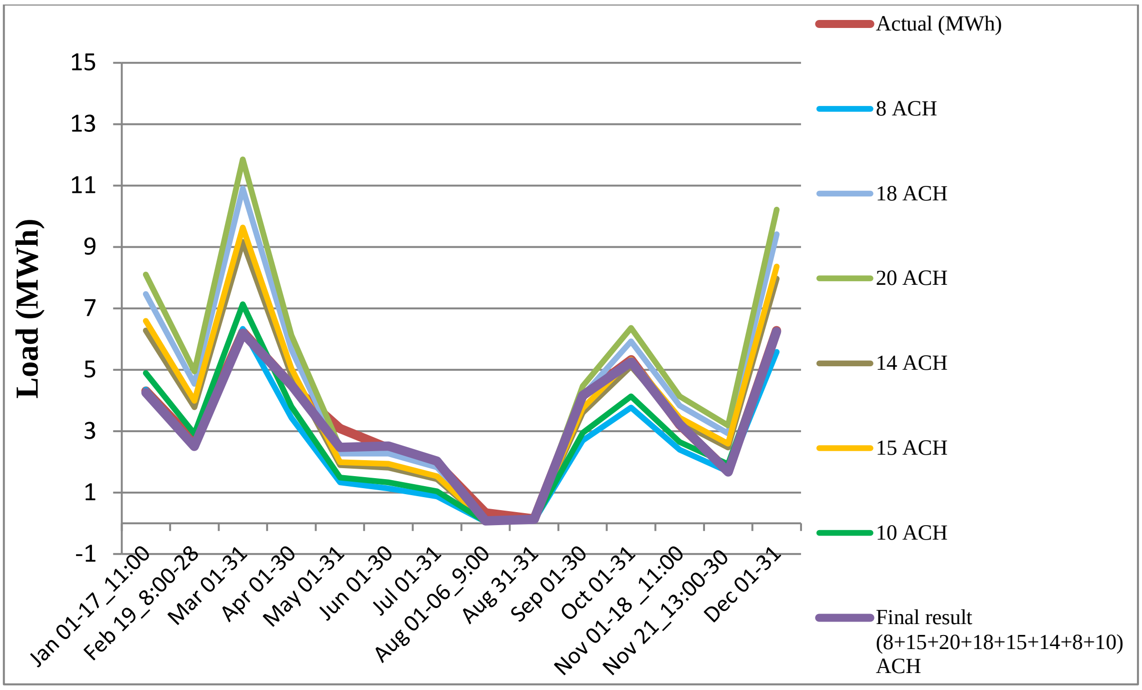


Figure 37. The iterative process to find the appropriate values for the extra infiltration rate during the field study.

To compare the results of final matched model with actual data in detail, the amount of monthly energy consumption obtained from model (purple colour) and actual data for the field study duration (red colour) are presented in Table 10. From this table, the IES-VE results show a great agreement with actual data recorded during the field study. The difference in total energy consumption is only 1.12 MWh which represents about 2.4% error. Having the model with low difference error means it is well positioned to be an excellent model for the retail store which will be reliable for further studies.

Table 10. IES-VE model and Actual energy consumption for the period of field study.

Actual	
Date	**MWh**
Jan 01-17_11:00	4.306357
Feb 19_8:00-28	2.664153
Mar 01-31	6.239218
Apr 01-30	4.498942
May 01-31	3.089064
Jun 01-30	2.447807
Jul 01-31	1.960423
Aug 01-06_9:00	0.337065
Aug 31-31	0.146458
Sep 01-30	4.150699
Oct 01-31	5.331116
Nov 01-18 _11:00	3.21869
Nov 21_13:00-30	1.698818
Dec 01-31	6.276045
Summed total	**46.36485**

IES-VE	
Date	**MWh**
Jan 01-17_11:00	4.25767
Feb 19_8:00-28	2.5076
Mar 01-31	6.1896
Apr 01-30	4.4948
May 01-31	2.4741
Jun 01-30	2.5127
Jul 01-31	2.0269
Aug 01-06_9:00	0.083393
Aug 31-31	0.1323
Sep 01-30	4.1591
Oct 01-31	5.2524
Nov 01-18 _11:00	3.238298
Nov 21_13:00-30	1.673264
Dec 01-31	6.2475
Summed total	**45.24962**

Before coating

After coating

After set-up process for energy consumption, to check the validity of the model the IES weather data input file was searched to find the highest dry bulb temperature which was 32°C on the 3rd of October at 13:30. The relative humidity for the selected temperature on the given time and date extracted from the IES weather file, was 23%. On the other hand, in the actual weather data (BOM) the similar pairs of dry bulb temperature and relative humidity readings was found for the 24th of September at 11:00 with the temperature of 30 °C and 24% relative humidity. As shown in Figure 38, these two days showing almost similar load profiles.

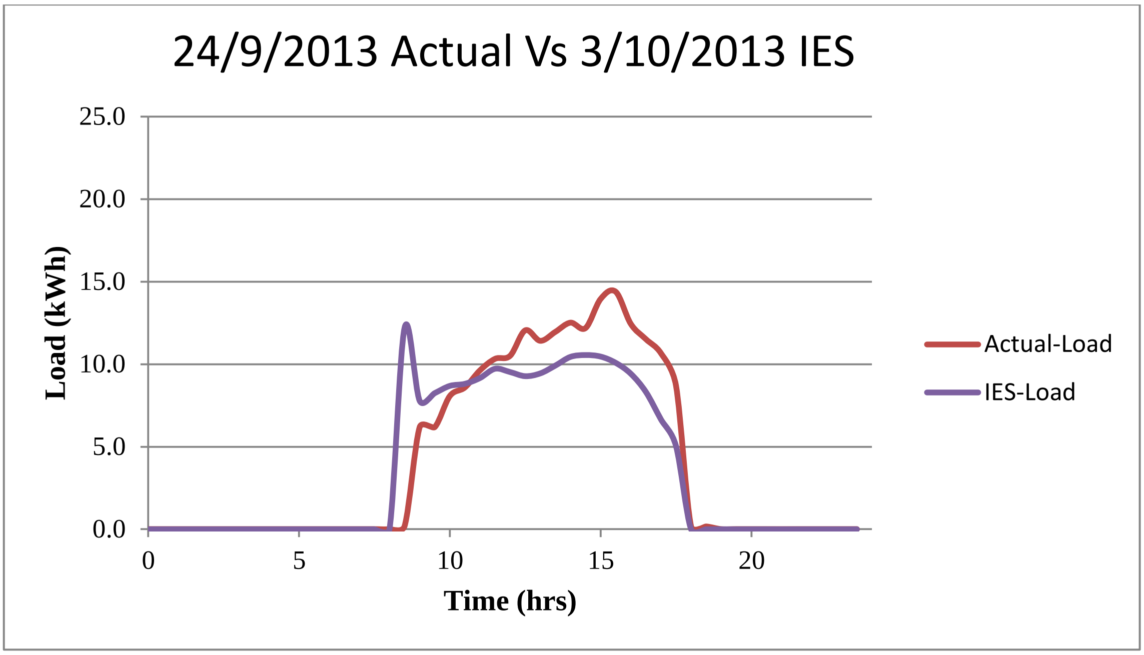


Figure 38. Comparison between actual and IES similarity in dry bulb temperature and relative humidity.

This graph indicates the load profiles are following the similar trend but due to difference in humidity and dry bulb temperature, are not exactly the same. Table 11 shows the data for these two load profiles and clarifies their differences in energy consumption. Also, the difference between dry bulb temperature and relative humidity for IES-VE and actual weather data are presented in Table 12 for the two aforementioned dates. As can be seen from this table for the highlighted times, the dry bulb temperature and relative humidity are almost the same. Furthermore, the similar power consumption can be observed in Table 11 for the relevant readings which are highlighted in this table as well. Therefore, these analyses show the validity of the model. Also, the validity of the model was confirmed in the same process for some other days and the daily energy consumption in the model simulation results and actual data were found to be matched properly depending on special infiltration rate for that date.

Table 11. The load data for 2 different days with similar humidity and dry bulb readings in highlighted times.

Time	Actual-load (kW)	IES-load (kW)
9	6.2	7.78
9.5	6.2	8.25
10	8.1	8.7
10.5	8.6	8.81
11	9.6	9.16
11.5	10.3	9.72
12	10.5	9.52
12.5	12.1	9.27
13	11.4	9.44
13.5	12.0	9.78
14	12.5	9.92
14.5	12.2	10.55
15	14.0	10.46
15.5	14.4	10.08
16	12.4	9.42
16.5	11.5	8.32
17	10.7	6.66
17.5	8.7	5.04
18	0.2	0

Table 12. Comparisons of IES-VE and actual weather temperature (°C) and relative humidity (%).

IES-VE				Actual			
Date	Time	Relative humidity	Dry bulb	Date	Time	Relative humidity	Dry bulb
3-Oct-13	0:00	88	21.3	24-Sep-13	0:00	88	18.8
	1:00	92	20.1		1:00	88	18
	2:00	87	20.7		2:00	92	16.3
	3:00	93	18.8		3:00	95	15.6
	4:00	95	18.1		4:00	96	16.6
	5:00	95	17.4		5:00	98	16.4
	6:00	92	18.1		6:00	98	16
	7:00	87	20.8		7:00	93	17.1
	8:00	71	23.7		8:00	74	21.1
	9:00	59	26		9:00	57	23.9
	10:00	47	28.7		10:00	39	26.5
	11:00	46	28.5		11:00	24	30
	12:00	41	30.1		12:00	34	30.4
	13:00	32	30.9		13:00	26	31.6
	14:00	23	32		14:00	25	32.2
	15:00	18	31.4		15:00	44	29.4
	16:00	14	29.9		16:00	49	28
	17:00	15	28		17:00	54	26.2
	18:00	17	25.8		18:00	56	25.1
	19:00	21	23.9		19:00	60	24.4
	20:00	18	22.3		20:00	59	24
	21:00	18	21.2		21:00	61	23
	22:00	13	19.8		22:00	62	21.9
	23:00	20	17.8		23:00	68	20.1

3.7 VALID MODEL ANALYSES FOR THE CASE STUDY

The validated model was used to study the effect of cool roof technology on annual energy saving for the case study. Furthermore, the case study was evaluated for different infiltration rates to observe the building performance in different conditions. The infiltration rate was changed to approach to the Green Star value that meets higher performance standard than the minimum regulatory requirements. This will lead to the maximum amount of energy saving for these buildings if a cool roof coating was applied. In other words, if the building condition was improved to achieve a Green Star rating, more savings would occur through the application of cool roofs on current case study.

3.8 VALID MODEL PREDICTION FOR OTHER AUSTRALIAN CLIMATE CITIES/ZONES

Extrapolation involves generalizing the results into the larger scale, identifying the potential energy savings that could be applied to similar building in different climate zones around Australia. Figure 39 shows different climate zones in Australia.

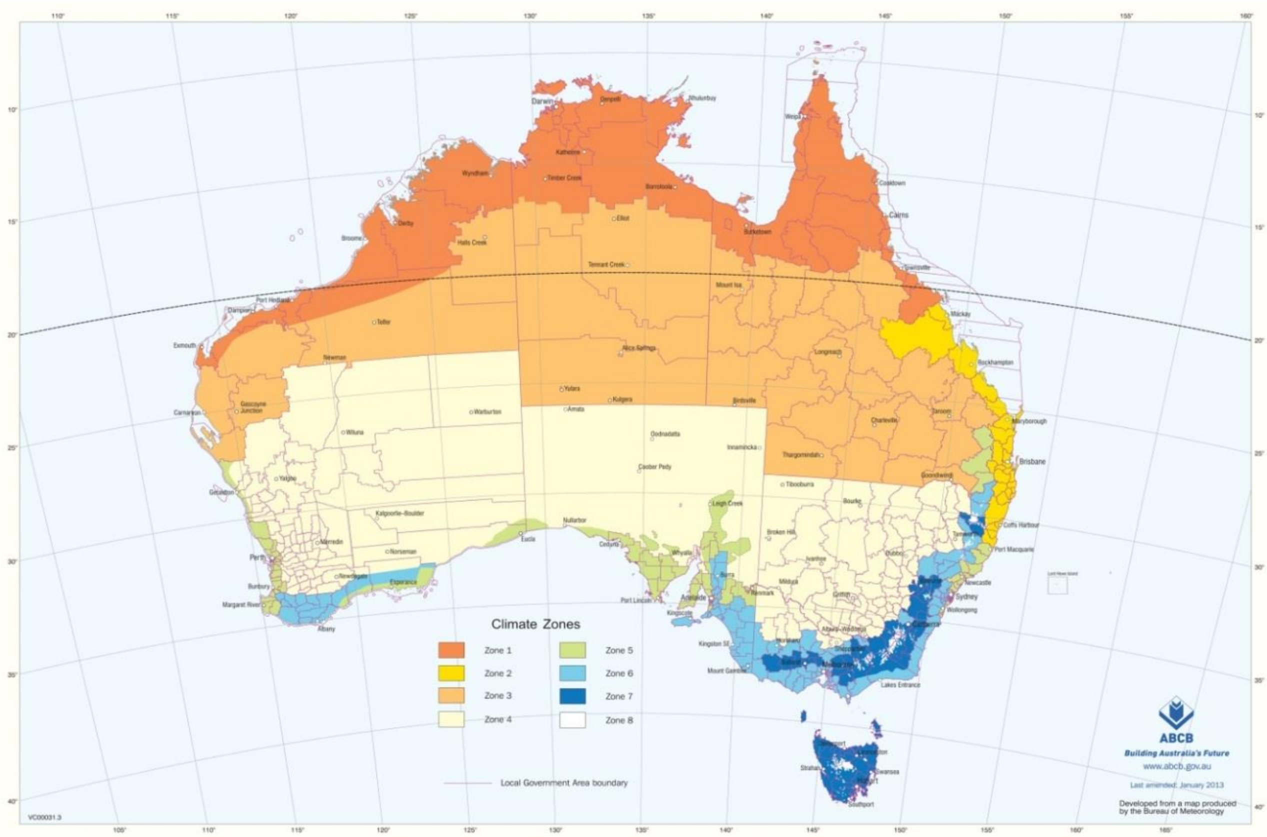


Figure 39. Zones map in Australia [78].

Different cities from these zones were selected for further analyses and simulations. These cities are selected based on available weather file input for IES-VE. Table 13 shows the selected cities in different climate zones.

Table 13. Selected climate zones and cities around Australia.

Climate Zone	Selected city	States	Climate
1	Darwin	NT	Hot humid summer, warm winter
2	Brisbane	QLD	Warm humid summer, mild winter
3	Alice Springs	NT	Hot dry summer, warm winter
4	Dubbo	NSW	Hot dry summer, cool winter
5	Sydney	NSW	Warm temperate
6	Melbourne	VIC	Mild temperate
7	Canberra	ACT	Cool temperate

The energy consumption difference before and after cool roof application in diverse climate zones of Australia can be calculated by changing the weather input file specific to each selected city in IES-VE. By running the simulations without cool roof application (before) and again with cool roof application (after), the effectiveness of this technology can be determined in different parts of Australia. These results can then be used in developing guidelines for the use of cool roof technology. The future work in cool roof application would be specified with respect to relevant zones in Australia.

Chapter 4: Result and Discussion

4.1 CASE STUDY ANALYSES BY VALIDATED MODEL

The field study data was not collected for a complete year before and after the cool roof coating was applied. So the annual energy consumption and temperature variation during one year before and after cool roof application was simulated by the validated model (see 4.1.1 and 4.1.2). The comparison of data from this simulation estimates the effect of cool roof on annual energy saving and temperature reduction. To provide an overview of the retail store model, the pictures of the developed model in IES-VE are presented in Figure 40 and Figure 41.

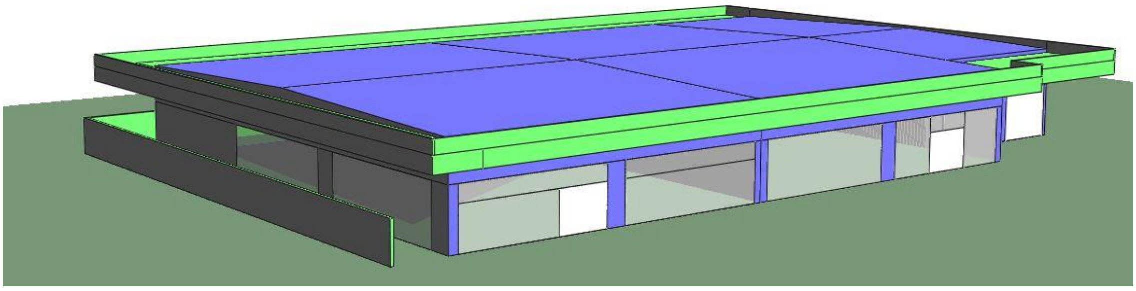


Figure 40. The retail store model in IES-VE software.

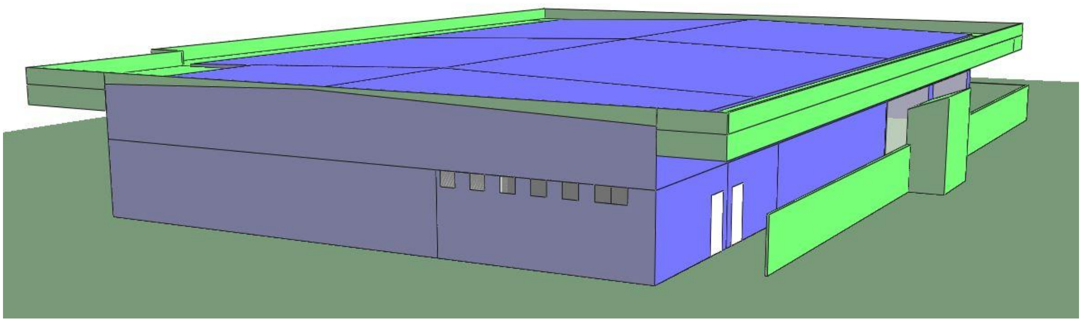


Figure 41. The retail store model in IES-VE software.

The final construction material characteristics (Table 14) were obtained after validation process. The building's external walls are categorized in three types. Type 2 and 3 are South

West and North West walls of the storage area which are made of concrete blocks and steel respectively, whilst Type 1 is representative of all other walls which are made of concrete panels. The ceiling void walls are all steel and Type 3. Features of different external wall types are presented also in the table. The detail specifications of validated model have been presented in Appendix B.

Table 14. The final characteristics of construction materials which are used in IES-VE after trial and error.

Construction	**Total R value** (m^2K/W)	**Total U value** (W/m^2K)	**Emissivity outside**	**Emissivity inside**	**Absorptance outside**	**Absorptance inside**
Roof (Before Coating)	0.3686	1.9660	0.25	0.05	0.8	0.15
Roof (After coating)	0.3686	1.9660	0.89	0.05	0.125	0.15
External Wall (type1)	0.2488	2.3878	0.89	0.85	0.8	0.7
External Wall (type2)	0.3922	1.7787	0.89	0.9	0.8	0.6
External Wall (type3)	0.0001	5.8789	0.5	0.5	0.8	0.8
Internal Fire Wall	2.3897	0.3774	0.9	0.9	0.55	0.55
Internal Partition	0.3175	1.7316	0.89	0.89	0.7	0.7
Suspended Ceiling	0.1786	2.6415	0.9	0.9	0.2	0.2
Floor	2.7488	0.3391	0.9	0.9	0.55	0.55
Glazing	0.1757	5.6102	0.84	0.84	-	-

4.1.1 Temperature simulation results

Table 15 presents the yearly IES-VE model results before and after cool coating for the number of hours that the temperature was less than 21°C, between 21-23 °C, and more than 23°C in each ceiling void i.e. ceiling void 1 (clothing store), ceiling void 2 (appliance store) and ceiling void 3 (storage). The comparison illustrates a general reduction in temperature in different ceiling voids after cool roof application. The total number of hours that the temperature was less than 21°C and in the range of 21-23°C increases about 26% and 29%, respectively. These results indicate that thermal comfort is improved by using a cool roof coating.

Furthermore, the number of hours that the temperature is between 23°C and 26°C in all ceiling voids increases by 21% indicating the ceiling voids are much cooler after cool roof application. In ceiling void 1 and 2 the number of hours that the temperature is between 26-29°C and 29-32°C reduces nearly 19% and 88% respectively. Temperatures higher than 32 °C were not found in the model after application of cool roof in the ceiling void of 1 and 2 whilst the number of hours decreases by 96% in ceiling void 3. The cooler ceiling void decreases the heat transfer into the stores which results in reducing the air-conditioning usage. Therefore, the lower cooling loads would be obtained to provide thermal comfort condition in the building due to the temperature reduction.

Table 16 and Figure 42 indicate the IES-VE model prediction for the ceiling void 1 air temperature before and after cool roof application for each month. As can be seen, the maximum reduction of maximum, minimum and mean temperature for different months was about 27%, 14% and 12% respectively. The results of these two tables indicate a significant reduction in temperatures inside the building by cool roof coating which has an important effect on energy saving by reducing the cooling load.

Table 15. Comparison of different number of temperature/hours in ceiling voids before and after cool roof application during the year.

Ceiling void 1-Clothing store										
Air temperature (°C) - hours in range					**Air temperature (°C) - hours in range**					
File	**Location**	**<= 21.00**	**>21.00 to <=23.00**	**> 23.00**	**File**	**Location**	**>23.00 to <=26.00**	**>26.00 to <=29.00**	**>29.00 to <=32.00**	**> 32.00**
Before coating	ceiling void 1	3206.5	1190.5	4363	**Before coating**	ceiling void 1	1648.5	1161	941.5	612
Air temperature (°C) - hours in range					**Air temperature (°C) - hours in range**					
File	**Location**	**<= 21.00**	**>21.00 to <=23.00**	**> 23.00**	**File**	**Location**	**>23.00 to <=26.00**	**>26.00 to <=29.00**	**>29.00 to <=32.00**	**> 32.00**
After coating	ceiling void 1	4056	1640.5	3063.5	**After coating**	ceiling void 1	2175.5	834.5	53.5	0
Difference Air temperature (°C) - hours in range					**Difference Air temperature (°C) - hours in range**					
File	**Location**	**<= 21.00**	**>21.00 to <=23.00**	**> 23.00**	**File**	**Location**	**>23.00 to <=26.00**	**>26.00 to <=29.00**	**>29.00 to <=32.00**	**> 32.00**
Before-After	ceiling void 1	-849.5	-450	1299.5	**Before-After**	ceiling void 1	-527	326.5	888	612

Ceiling void 2-Appliance store										
Air temperature (°C) - hours in range					**Air temperature (°C) - hours in range**					
File	**Location**	**<= 21.00**	**>21.00 to <=23.00**	**> 23.00**	**File**	**Location**	**>23.00 to <=26.00**	**>26.00 to <=29.00**	**>29.00 to <=32.00**	**> 32.00**
Before coating	ceiling void 2	3120.5	1200.5	4439	**Before coating**	ceiling void 2	1679	1119.5	896	744.5
Air temperature (°C) - hours in range					**Air temperature (°C) - hours in range**					
File	**Location**	**<= 21.00**	**>21.00 to <=23.00**	**> 23.00**	**File**	**Location**	**>23.00 to <=26.00**	**>26.00 to <=29.00**	**>29.00 to <=32.00**	**> 32.00**
After coating	ceiling void 2	4087	1515	3158	**After coating**	ceiling void 2	1991	1003	164	0
Difference Air temperature (°C) - hours in range					**Difference Air temperature (°C) - hours in range**					
File	**Location**	**<= 21.00**	**>21.00 to <=23.00**	**> 23.00**	**File**	**Location**	**>23.00 to <=26.00**	**>26.00 to <=29.00**	**>29.00 to <=32.00**	**> 32.00**
Before-After	ceiling void 2	-966.5	-314.5	1281	**Before-After**	ceiling void 2	-312	116.5	732	744.5

Ceiling void 3-Storage										
Air temperature (°C) - hours in range					**Air temperature (°C) - hours in range**					
File	**Location**	**<= 21.00**	**>21.00 to <=23.00**	**> 23.00**	**File**	**Location**	**>23.00 to <=26.00**	**>26.00 to <=29.00**	**>29.00 to <=32.00**	**> 32.00**
Before coating	ceiling void 3	3608	1089	4063	**Before coating**	ceiling void 3	1365.5	880	762.5	1055
Air temperature (°C) - hours in range					**Air temperature (°C) - hours in range**					
File	**Location**	**<= 21.00**	**>21.00 to <=23.00**	**> 23.00**	**File**	**Location**	**>23.00 to <=26.00**	**>26.00 to <=29.00**	**>29.00 to <=32.00**	**> 32.00**
After coating	ceiling void 3	4385	1335.5	3039.5	**After coating**	ceiling void 3	1517	1064.5	414	44
Difference Air temperature (°C) - hours in range					**Difference Air temperature (°C) - hours in range**					
File	**Location**	**<= 21.00**	**>21.00 to <=23.00**	**> 23.00**	**File**	**Location**	**>23.00 to <=26.00**	**>26.00 to <=29.00**	**>29.00 to <=32.00**	**> 32.00**
Before-After	ceiling void 3	-777	-246.5	1023.5	**Before-After**	ceiling void 3	-151.5	-184.5	348.5	1011

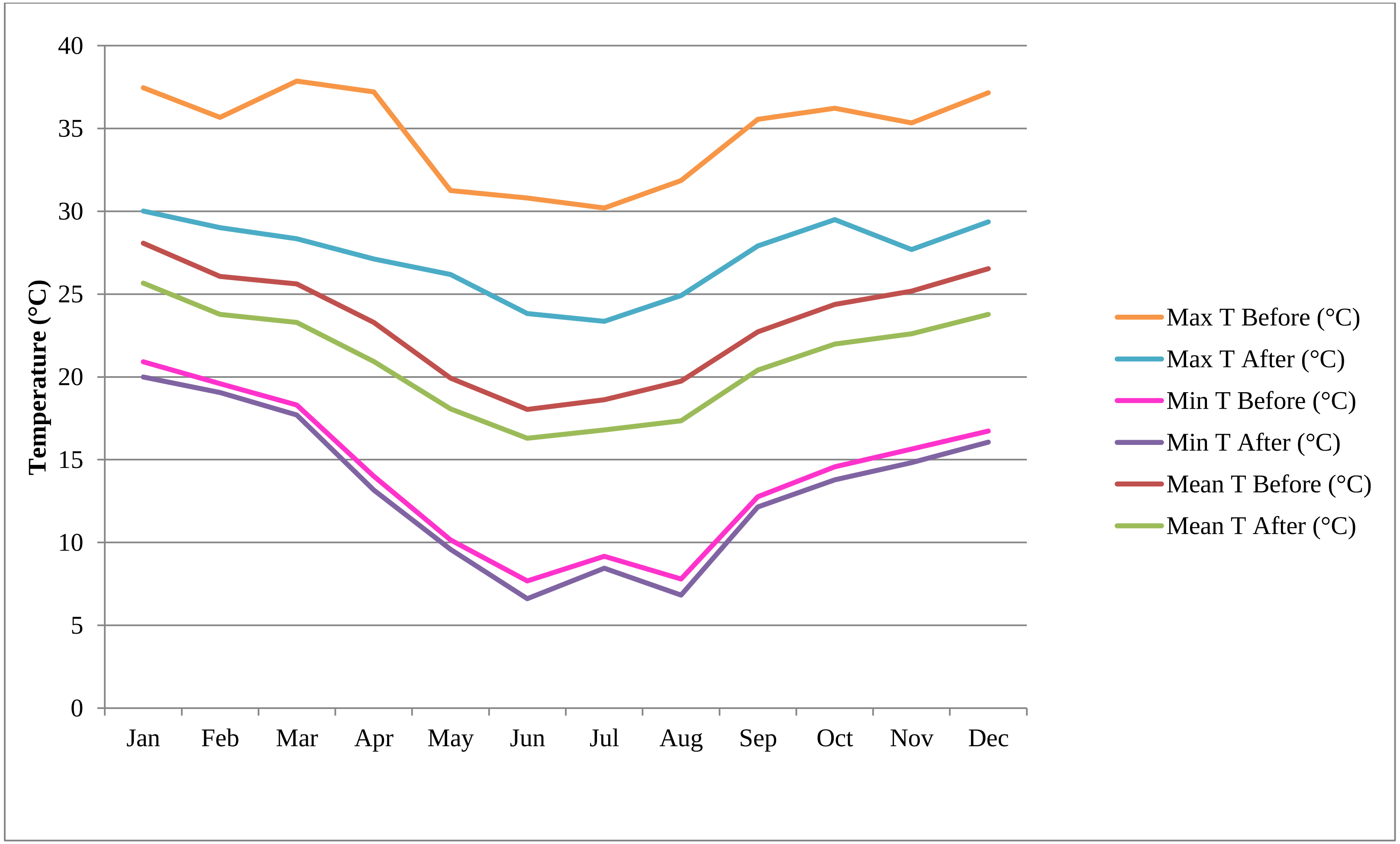


Figure 42. Monthly air temperatures before and after cool roof coating for ceiling void1 (clothing store) in IES-VE model with green star infiltration (1 $m^3/h/m^2$@50 Pa or 0.33 ACH@50 Pa).

Table 16. Monthly air temperatures before and after cool roof coating for ceiling void1 (clothing store) in IES-VE model with green star infiltration (1 $m^3/h/m^2$@50 Pa or 0.33 ACH@50 Pa).

Months	Max T Before (°C)	Max T After (°C)	Difference %	Min T Before (°C)	Min T After (°C)	Difference %	Mean T Before (°C)	Mean T After (°C)	Difference %
Jan	37.46	30.02	19.86	20.72	19.84	4.25	28.02	25.63	8.53
Feb	35.66	29.05	18.54	19.41	18.89	2.68	26	23.73	8.73
Mar	37.85	28.34	25.13	18.06	17.48	3.21	25.54	23.25	8.97
Apr	37.19	27.12	27.08	13.67	12.84	6.07	23.17	20.84	10.06
May	31.24	26.18	16.20	9.81	9.26	5.61	19.77	17.93	9.31
Jun	30.79	23.81	22.67	7.22	6.19	14.27	17.84	16.13	9.59
Jul	30.2	23.35	22.68	8.81	8.12	7.83	18.42	16.62	9.77
Aug	31.83	24.92	21.71	7.29	6.36	12.76	19.53	17.17	12.08
Sep	35.54	27.9	21.50	12.45	11.85	4.82	22.6	20.31	10.13
Oct	36.2	29.51	18.48	14.26	13.5	5.33	24.28	21.91	9.76
Nov	35.31	27.68	21.61	15.36	14.57	5.14	25.08	22.54	10.13
Dec	37.15	29.36	20.97	16.46	15.82	3.89	26.44	23.7	10.36

4.1.2 Energy consumption simulation results

A large portion of energy waste in buildings is due to poor building construction. It is important to investigate the appropriate methods to reduce such losses in the building because it has a large accumulative effect on energy use. Therefore, improving the guidelines and rules based on energy saving in relevant building codes should be placed on the agenda. Usually, Australian buildings perform poorly in terms of air leakage compared to the buildings in other countries [76]. The retail store case study confirms to this statement and has poor construction which magnifies the leakage. Moreover, the tenants tendency to leave the entrance door open exacerbates the amount of energy used compared to the same building with normal entrance door opening and closing (ie. reduced infiltration). The validated model was also used to calculate the amount of monthly energy consumption before and after cool coating for a year. The results were summarised in Table 17 for the case study.

Table 17. Energy use before and after cool roof coating for the retail store.

Before coating	
Date	**MWh**
Jan 01-31	9.01
Feb 01-28	5.91
Mar 01-31	6.46
Apr 01-30	5.19
May 01-31	2.52
Jun 01-30	2.47
Jul 01-31	1.96
Aug 01-31	1.42
Sep 01-30	4.16
Oct 01-31	5.25
Nov 01-30	6.16
Dec 01-31	6.57
Summed total	**57.09**

After coating	
Date	**MWh**
Jan 01-31	8.73
Feb 01-28	5.67
Mar 01-31	6.19
Apr 01-30	4.5
May 01-31	2.47
Jun 01-30	2.51
Jul 01-31	2.03
Aug 01-31	1.29
Sep 01-30	3.94
Oct 01-31	4.53
Nov 01-30	5.88
Dec 01-31	6.25
Summed total	**53.99**

The difference between total energy consumption before and after cool roof coating was 3.1 MWh which is only about a 5.4% reduction in energy consumption. This amount of saving is not representative of the full benefit of cool roof application precisely. The advantage can be highlighted better if it is assumed that the tenants did not leave the door open, or the entrance door was replaced by an automatic door. To demonstrate this, the extra infiltration rate was removed from the model and only the infiltration of 2 ACH@50 Pa, approximate infiltration rate for a leaky commercial building in Brisbane was considered. The updated simulation results are presented in Table 18.

Table 18. Energy use before and after cool roof coating for a leaky commercial building in Brisbane.

Before coating		**After coating**	
Date	**MWh**	**Date**	**MWh**
Jan 01-31	3.52	Jan 01-31	3.24
Feb 01-28	2.48	Feb 01-28	2.24
Mar 01-31	2.7	Mar 01-31	2.43
Apr 01-30	1.82	Apr 01-30	1.56
May 01-31	0.87	May 01-31	0.7
Jun 01-30	0.47	Jun 01-30	0.37
Jul 01-31	0.52	Jul 01-31	0.38
Aug 01-31	0.88	Aug 01-31	0.65
Sep 01-30	1.5	Sep 01-30	1.25
Oct 01-31	1.92	Oct 01-31	1.64
Nov 01-30	2.1	Nov 01-30	1.80
Dec 01-31	2.61	Dec 01-31	2.28
Summed total	**21.39**	**Summed total**	**18.55**

The amount of energy use before coating in this case is about 36 MWh less than the previous results for the case study due to occupant behaviour (left the door open).Therefore, a significant energy saving can be achieved if the building tenants changes their behavioral pattern. Extra saving of 13% is obtained resulting from cool roof application which is the annual energy saving of about 2.84 MWh in this case.

Comparison with best practice Green Star building

The cool roof application could be more effective if building conditions were aligned with the best practice outcome for a target Green Star building. In other words, if the building envelope characteristics were chosen from the best practice outcome of the Green Buildings Council of Australia (GBCA), the maximum energy saving will be obtained by cool roof application. For example, without any extra infiltration and by replacing the infiltration rate of a best practice outcome for retail super stores which is 1 m3/h/m2@50 Pa or 0.33 ACH@50 Pa [79], the building has been modelled as Green Star building in terms of leakage. Table 19 shows the simulation results with Green Star infiltration rates. From this table, the amount of energy saving is 3.015 MWh or about 18% annual energy saving by cool coating.

Table 19. Energy use before and after cool roof coating for commercial building using green star infiltration rate (1 m3/h/m2@50 Pa or 0.33 ACH@50 Pa) in Brisbane.

Before coating	
Date	**MWh**
Jan 01-31	2.4
Feb 01-28	1.79
Mar 01-31	1.94
Apr 01-30	1.49
May 01-31	0.84
Jun 01-30	0.46
Jul 01-31	0.56
Aug 01-31	0.93
Sep 01-30	1.31
Oct 01-31	1.59
Nov 01-30	1.66
Dec 01-31	1.98
Summed total	**16.95**

After coating	
Date	**MWh**
Jan 01-31	2.11
Feb 01-28	1.54
Mar 01-31	1.66
Apr 01-30	1.22
May 01-31	0.65
Jun 01-30	0.32
Jul 01-31	0.39
Aug 01-31	0.68
Sep 01-30	1.05
Oct 01-31	1.3
Nov 01-30	1.36
Dec 01-31	1.65
Summed total	**13.93**

Furthermore, the comparison of the energy consumption after coating for the best practice model with the energy consumption before coating for the basic simulation (Table 17) have revealed a significant energy consumption reduction of 43.16 MWh annually for this case study. In other words, the amount of energy use in the current case study for before and after cool roof coating are about 3.4 and 3.9 times higher than the same commercial building with green star air infiltration rate (1 $m^3/h/m^2$@50 Pa or 0.33 ACH@50 Pa). Therefore, if the leakage for this case study or a similar commercial building in Brisbane could be improved to Green Star infiltration target and also inappropriate method of entrance door use by occupant's behavior to attract customers is modified and cool roof coating is applied, it could be obtained the highest energy saving value at about 76% which is very significant.

4.2 EXTRAPOLATION RESULTS

It is advantageous to look at the effect of cool roof application for this type of commercial building all over Australia to see how effective this technology is in different climate zones. From Figure 43, the zones can be categorised in two general parts of hot (zone 1-3) and mild (zone 4-7). To this end, the 2012 IES-VE weather files for most Australian cities are available and this used to investigate energy saving due to cool roofs in different Australian climates. For this analyses, simulations was performed for two types of commercial building: a leaky building (infiltration of 2 ACH@50 Pa) and a well-sealed building (infiltration of 1 $m^3/h/m^2$@50 Pa which is equal to 0.33 ACH@50 Pa). For the leaky commercial building, the trend of energy consumption before and after cool roof coating is shown in Table 20 for selected cities.

Zone	Description
1	Hot humid summer, warm winter
2	Warm humid summer, mild winter
3	Hot dry summer, warm winter
4	Hot dry summer, cool winter
5	Warm temperate
6	Mild temperate
7	Cool temperate
8	Alpine

Figure 43. Australian climate zones description [80].

Table 20. IES annual energy use prediction for the leaky commercial building in zones of Australia.

City	Zone	Before coating (MWh/year)	After coating (MWh/year)	Difference (MWh/year)	Difference (%)	Saving (kWh/year/m^2)
Darwin	1	47.83	44.38	3.44	7.20	8.36
Brisbane	2	19.78	17.12	2.67	13.48	6.47
Alice Springs	3	22.82	19.42	3.40	14.90	8.25
Dubbo	4	12.86	10.92	1.93	15.02	4.69
Sydney	5	10.69	8.78	1.91	17.84	4.63
Melbourne	6	5.62	4.48	1.14	20.31	2.77
Canberra	7	6.95	4.93	2.02	29.10	4.91

As Table 20 indicates for a leaky commercial building, the percentages of energy difference for cities in mild climate zone are higher than cities in hot climate zone. However, these percentages should not be misunderstood. In mild climate zone the energy consumption before coating is reasonably low and the actual difference caused by the cool roof will be reflected considerably in percentage reduction. On the other hand, the difference in energy consumption (and therefore costs and greenhouse gas reduction) for cities in hot climate zones is higher than in mild climate. It confirms the greater potential for cool roof application in hot climates. Also, hot climate zone have greater savings per square meter compared to the mild climate zone. As the zones progress towards mild climates in the table, the saving per square meter is decreasing. It should be mentioned that the energy here is the cooling energy only. Any possible heating penalty in mild climates should be taken into the account in order to know the actual benefit of cool roof application in those climates.

Table 21 shows the annual energy consumption for the target air leakage commercial building in different cities throughout Australian climate zones. Cool roof application has different effects in various climates. Average total energy saving (difference) in mild climate zone ((Dubbo+Melbourne+Sydney+Canberra) is 2.06 MWh and is 3.37 MWh for hot climate zone (Darwin+Brisbane+Alice Springs). It means this technology is more beneficial in hot climates than in mild climates while there is no heating penalty in hot climates which confirms by the presented literature.

Comparison of Table 20 and Table 21 reveals that the amount of energy saving in each city in different climate zones for the target air leakage building is higher than for the leaky building. This means the less leaky the building is, the more saving can be obtained by cool roof application. Furthermore, due to the proper construction of the targeted commercial building the amount of energy consumption in cold seasons is lower than leaky commercial building which means the heating penalty of cool roof coating should also be lower. Therefore, the cool roof application can be more effective in targeted air leakage commercial buildings compared to the leaky and poorly constructed buildings.

Table 21. IES annual energy use prediction for the targeted air leakage (1 $m^3/h/m^2$@50 Pa or 0.33 ACH@50 Pa) commercial buildings in climate zones of Australia in 2012.

City	**Zone**	**Before coating (MWh/year)**	**After coating (MWh/year)**	**Difference (MWh/year)**	**Difference (%)**	**Saving ($kWh/year/m^2$)**
Darwin	1	31.65	28.11	3.54	11.18	8.59
Brisbane	2	15.46	12.57	2.89	18.69	7.01
Alice Springs	3	19.19	15.52	3.67	19.13	8.91
Dubbo	4	11	8.76	2.23	20.3	5.42
Sydney	5	9.25	6.98	2.27	24.56	5.51
Melbourne	6	5.31	3.83	1.48	27.9	3.6
Canberra	7	6.60	4.05	2.55	38.64	6.19

From Table 20 and Table 21, Darwin has the largest energy consumption before coating and highest energy saving per square meter among the selected cities in different Australian climate zones. To investigate the potential of energy saving in Darwin, the hottest day from IES-VE weather file was found and the simulation results for that day extracted and presented here separately. The maximum wet-bulb temperature in IES-VE input weather file for Darwin is on 1st of February at 16:00 which is 27.52 °C. Figure 44 represents energy consumption profiles for before and after cool roof coating for 1st of February. The simulation results for the commercial building with target air leakage shows that the difference between total energy consumption before and after coating is 17.56 kW which is about 8.62% energy saving. These results prove the great potential of cool roof application on the commercial buildings in hot days.

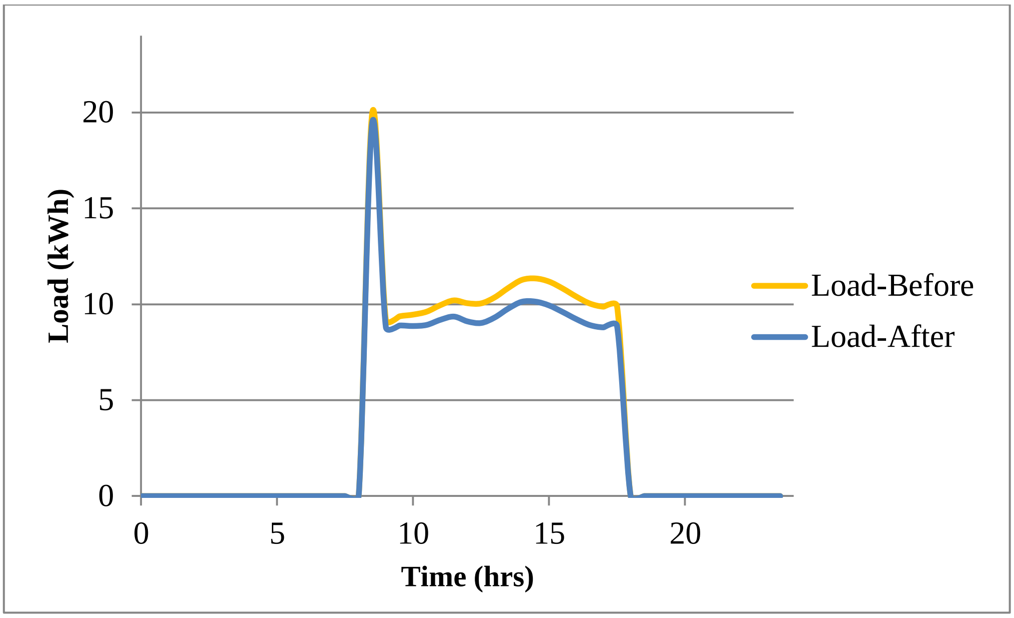


Figure 44. The load profiles of before and after cool coating for the commercial building with target air leakage on Feb 1st in Darwin.

The key outcomes of the simulation results of the case study applicable for similar commercial buildings are as follow:

1. Cool roof application on commercial buildings could reduce energy consumption in Australia, whether they are leaky or with acceptable air leakage.
2. Application of cool coating should be initiated in hot climates. The government policy to make cool roof application mandatory for buildings similar to the case study in hot climates is recommended. Consequently, a considerable amount of energy could be saved in those areas.
3. Some leaky or poorly constructed buildings would need a considerable expenditure into them to improve their quality to achieve green star buildings status. The owners would be reluctant to spend to improve the building structures for different reasons. Some of these reasons would be high expense, loss of income through down time, and disruption to the business. In these cases, they still could have significant energy saving by cool roof application on their current building. Furthermore with a limited budget further savings could be achieved on top of the cool roof application by fixing the building leakage. For instance, in Darwin, the energy saving by cool roof application is about 11.2% reduction in energy consumption and almost 34% more reduction could be obtained in energy consumption before cool roof application by improvements to the target leakage point.

4. Comparing the results after cool roof application for both types of buildings shows that cool roof technology using Green Star infiltration recommendation could reduce its energy consumption more than the leaky one and it has a greater influence on those types of buildings. For example in Darwin, after the cool roof application, the building which fixed the leakage has a 37% more saving in the amount of energy use than the leaky commercial building.
5. The percent of energy savings for buildings is sometimes not significant, however, the amount of energy saving remains significant when expressed in terms of saving per square meter.

4.2.1 CO_2 emission

Reducing carbon dioxide (CO_2) emission is crucial for contributing to environmental protection and sustainable development [81]. It would be interesting to know how cool roof technology could decrease CO_2 emission in each climate zone in Australia. For assessing this, the results are extracted from IES-VE simulation before and after cool roof application on the same commercial building in different zones/cities. Table 22 and Table 23 show the CO_2 emissions and its reduction as a result of cool roof application in the leaky and the target air leakage commercial building, respectively. These tables show more CO_2 emission reduction due to more energy saving. Therefore, the CO_2 emission reduction is higher for the building with target air leakage. The amount of CO_2 reduction in Alice Spring and Darwin are the highest, however, the maximum percentage of reduction is for Canberra. Furthermore, the total CO_2 emission reductions in these seven cities for leaky and targeted air leakage commercial building are 17,377 kg CO_2 and 19,507 kg $CO_{2,}$ respectively. These values correspond to taking about three and four vehicles out of the road each year respectively [82]. Therefore, the potential of vast application of cool roof technology for CO_2 emission reduction can be understood from this comparison.

Table 22. Total IES CO_2 emission prediction for the leaky commercial building in different cities in climatic zones of Australia.

City	Zone	Emission Before coating (kg CO_2)	Emission After coating (kg CO_2)	Emission Reduction (kg CO_2)	Emission Reduction (%)
Darwin	1	50833	47230	3603	7
Brisbane	2	21573	18776	2797	13
Alice Springs	3	25984	22376	3608	14
Dubbo	4	14320	12290	2030	14
Sydney	5	12038	10031	2007	17
Melbourne	6	6669	5471	1198	18
Canberra	7	8151	6017	2134	26

Table 23. Total IES CO_2 emission prediction for the target air leakage (1 $m^3/h/m^2$@50 Pa or 0.33 ACH@50 Pa) commercial building in different cities in climatic zones of Australia.

City	Zone	Emission Before coating (kg CO_2)	Emission After coating (kg CO_2)	Emission Reduction (kg CO_2)	Emission Reduction (%)
Darwin	1	33879	30177	3702	11
Brisbane	2	16958	13934	3024	18
Alice Springs	3	21021	17174	3847	18
Dubbo	4	12281	9946	2335	19
Sydney	5	10456	8078	2378	23
Melbourne	6	6331	4781	1550	24
Canberra	7	7685	5014	2671	35

The IES-VE CO_2 emission simulation results are based on national calculation methodology (NCM) of CO_2 emission factor in UK [83]. The CO_2 emission reduction calculation depends on the source of electricity generation. Therefore, it would be different for Australia with respect to the electricity generation technology utilised in each state. The National Greenhouse Gas Inventory released a report detailing the different emission factors for different states of Australia regarding their source of electricity generation in each state. Table 24 illustrates the emission factors regarding the source of electricity generation in Australia. The CO_2 emission reduction was modified for Australia based on these values. Table 25 and Table 26 present the emission reduction for the leaky and target air leakage commercial building using the emission factor of Australia.

Table 24. CO_2 emission factors-consumption of purchased electricity by end users in Australia-2014 [84].

State	NSW	ACT	VIC	QLD	SA	WA	TAS	NT
Emission factor (kg CO_2-e/kWh)	0.99	0.99	1.34	0.93	0.72	0.83	0.23	0.78

Table 25. Total CO_2 emission reduction for the leaky commercial building in different cities in climatic zones of Australia.

City	Zone	Coefficient ($kgCO_2$/kWh)	Energy Saving (kWh)	Emission Reduction (kg CO_2)
Darwin	1	0.78	3444.6	2686.8
Brisbane	2	0.93	2666.2	2479.6
Alice Springs	3	0.78	3401.1	2652.9
Dubbo	4	0.99	1931.4	1912.1
Sydney	5	0.99	1906.6	1887.5
Melbourne	6	1.34	1142	1530.3
Canberra	7	0.99	2023.8	2003.6

Table 26. Total CO_2 emission reduction for the target air leakage (1 $m^3/h/m^2$@50 Pa or 0.33 ACH@50 Pa) commercial building in different cities in climatic zones of Australia.

City	Zone	Coefficient ($kgCO_2/kWh$)	Energy Saving (kWh)	Emission Reduction (kg CO_2)
Darwin	1	0.78	3539	2760.4
Brisbane	2	0.93	2890.4	2668.1
Alice Springs	3	0.78	3671.2	2863.5
Dubbo	4	0.99	2232.4	2210.1
Sydney	5	0.99	2272.2	2249.5
Melbourne	6	1.34	1482.1	1968.0
Canberra	7	0.99	2550.9	2525.4

Comparison of Table 22-Table 23 and Table 25-Table 26 reveals that CO_2 emissions estimated by IES are different from those calculated using the emission factors for specific states in Australia. This is because IES uses some generic assumptions which conform to the national calculation methodology (NCM) for the UK. Therefore, a more specific emission factors are required based on the specific region in which buildings exist.

4.3 RECOMMENDATION FOR BUILDING CODE

Some countries have building regulations to specify the requirements verification for infiltration rate in any type of building, however, there are no minimum infiltration rates requirement in Australia [76]. Air infiltration rate is a very sensitive factor in building energy performance and simulations [76, 77]. By changing the infiltration rate in simulation software, different values of energy consumption in the building would be predicted. The National Construction Code of Australia (NCCA) does not release a clear permeable air limitation for different types of buildings. It seems the limitation of the Australian building regulation is not as serious as some other countries such as UK. For example, the airtightness requirements for different types of buildings are clearly presented in UK Building Regulation-L [76]. This study has shown that tighter air infiltration rates have the great impact on energy savings by cool roof technology. Therefore, it strongly recommended that consideration should be given to improve the building code of Australia (BCA) for airtightness and also R-values in the future building regulations.

Chapter 5: Conclusion & Recommendations

This study was undertaken based on a methodology that combined actual field data and the use of a building energy simulation software package (IES-VE). The main target of this research was to quantify the annual electricity savings of applying cool roof technology to a common type of commercial building in Australia. Based on analysis of the case study results, both indoor monitoring and the IES predictions proved the effect of cool roof coating in mitigating the thermal conditions; the temperature calculated reduction of 16-27% was reported for the monthly maximum temperature in the clothing store ceiling void. The number of hours the temperature was in the set point range (21°C-23°C) increased by nearly 29% after cool roof application which means less energy was required for cooling. The results of the IES-VE simulation model revealed that a commercial building with variable leakage, could have a widely different percentage of energy saving. In other words, annual energy savings generated by the cool roof application effect on a leaky commercial building with the entrance door chaotically left open to attract the customers, is only 5.5% (reduced from 57.03 to 53.99 MWh). This amount could increase to 13.3% (reduced from 21.39 to 18.55 MWh) by not leaving the door open, making it possible to achieve an energy consumption reduction of 18% (reduced from 16.95 to 13.93 MWh), if the commercial building leakage could be fixed to the specifications in the Green Building Council of Australia (GBCA). The targeted air leakage commercial building consume energy about 74% less than the current case study after cool roof coating in a year which is equal to about 40 MWh a year.

Additional energy simulations were performed to generalise the simulation results for different cities in seven climates of Australia and cool roofs were predicted to create savings in the range of 7% (reduced from 47.83 to 44.38 MWh) to 30% (reduced from 6.95 to 4.93 MWh) and 11% (reduced from 31.65 to 28.11 MWh) to 39% (reduced from 6.60 to 4.05 MWh) for a leaky and the targeted air leakage commercial building, respectively. The lower percentage is for hot climates which accounted for the larger amount of energy consumption reduction since their energy consumption before cool roof application is high. The buildings in mild climates consume moderately low energy for cooling; therefore, their saving percentage created by cool roof coating is high. Generally, cool roof technology is effective on large-one-storey commercial buildings in both the hot and mild climates of Australia; however in a mild climate the heating penalty should be taken into consideration.

To find the environmental benefit of the extrapolated results, the CO_2 emission reduction due to the cool roof application in different climate zones of Australia was analysed. The amount of CO_2 emission reduction in Alice Spring and Darwin are the highest, however, the maximum percentage of reduction is for Canberra. Furthermore, from this study the potential of vast application of cool roof technology for CO_2 emission reduction is recommended.

This information was an important step towards the development of a guideline for cool roof technology use in Australia. The results of this study were obtained based on large single-storey commercial buildings. The key findings which can contribute to design a guideline are:

- Hot climate zones in Australia with high value of energy consumption (zones 1-3) are the first priority for energy saving with application of cool roof technology.
- Installing the automatic doors or indirect entrance space design is strongly recommended due to their effect on infiltration rate which is found to be very important for energy savings.
- Heating penalty should be investigated in mild climates (zones 4-7) for precise estimation of cool roof technology effects on energy saving in similar commercial buildings.
- In a variety of buildings with low cooling load requirements such as storages and industrial buildings, or in specific structures such as some reservoirs this technology can be employed effectively.
- Further researches are required for other building typology in Australia to provide a comprehensive database for developing the guideline of cool roof application.

It will be advantageous to undertake future research on aspects related to cool roof application which go beyond the scope of this research. This study focused primarily on the cooling load saving that could be achieved in a large single-storey commercial building in different climates of Australia. Future research is required to evaluate the benefits of the widespread use of cool roof coating on a similar building, particularly Coles or Woolworth throughout the region. As a result, the amount of energy saving by this technique could be beneficial for the main electricity feeder in a region.

Knowing the effect of climate change over the past 20 years on cool roof application benefits would be an issue which could open different perspectives to look at in cool roof technology.

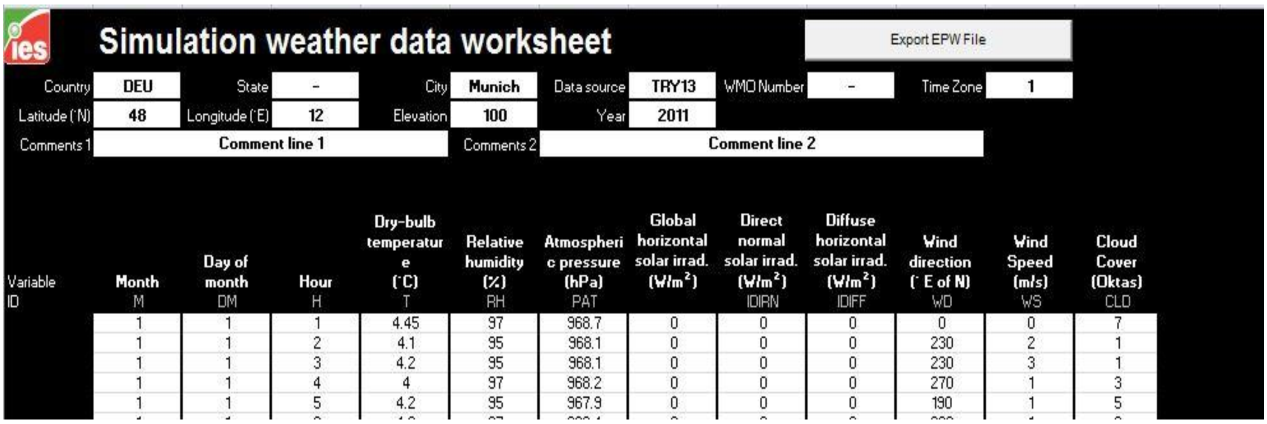
Further scope for the investigation would be to assess the influence of cool roof technology on a commercial building type on the heat island effect by roof surface temperature reduction.

All these aspects will be addressed in forthcoming research to estimate energy reduction and other environmental benefits of cool roof application.

Appendices

Appendix A

The following figure represents the IES weather data work sheet which its output is weather input file in fwt or .epw format suitable for IES-VE. By using this, the custom weather data input file will be created. For this, the following information was required; dry-bulb temperature, relative humidity, atmospheric pressure, global horizontal solar irradiance, direct normal solar irradiance, diffuses horizontal solar irradiance, wind direction, wind speed and cloud covers in hourly format. Figure A-1 shows the simulation weather data work sheet for creating a weather file in .epw format usable in IES-VE software.


Simulation weather data worksheet

Export EPW File

Country: DEU | State: - | City: Munich | Data source: TRY13 | WMO Number: - | Time Zone: 1

Latitude (°N): 48 | Longitude (°E): 12 | Elevation: 100 | Year: 2011

Comments 1: Comment line 1 | Comments 2: Comment line 2

Variable ID	Month M	Day of month DM	Hour H	Dry-bulb temperature (°C) T	Relative humidity (%) RH	Atmospheric pressure (hPa) PAT	Global horizontal solar irrad. (W/m²)	Direct normal solar irrad. (W/m²) IDIRN	Diffuse horizontal solar irrad. (W/m²) IDIFF	Wind direction (° E of N) WD	Wind Speed (m/s) WS	Cloud Cover (Oktas) CLD
	1	1	1	4.45	97	968.7	0	0	0	0	0	7
	1	1	2	4.1	95	968.1	0	0	0	230	2	1
	1	1	3	4.2	95	968.1	0	0	0	230	3	1
	1	1	4	4	97	968.2	0	0	0	270	1	3
	1	1	5	4.2	95	967.9	0	0	0	190	1	5

Figure A-1. Weather data worksheet for making weather file in .epw format.

Appendix B

Table B-1. IES-VE input file.

IES-VE input file			Room 1 (Clothing store)	Room 2 (Appliance store)	Room 3 (Storage)	Room 4 (Bathroom)	Ceiling void 1	Ceiling void 2	Ceiling void 3
Internal gains	Fluorescent lighting	Max sensible gain	5460 Watts	1050 Watts	546 Watts	234 Watts	-	-	-
		Max power consumption	5460 Watts	1050	546 Watts	234 Watts			
		Radiant fraction	0.45	0.45	0.45	0.45			
		Profile	HVAC	OFF	HVAC	HVAC			
	People	density	10	6	-	-			
		Max sensible gain	90 W/person	90 W/person					

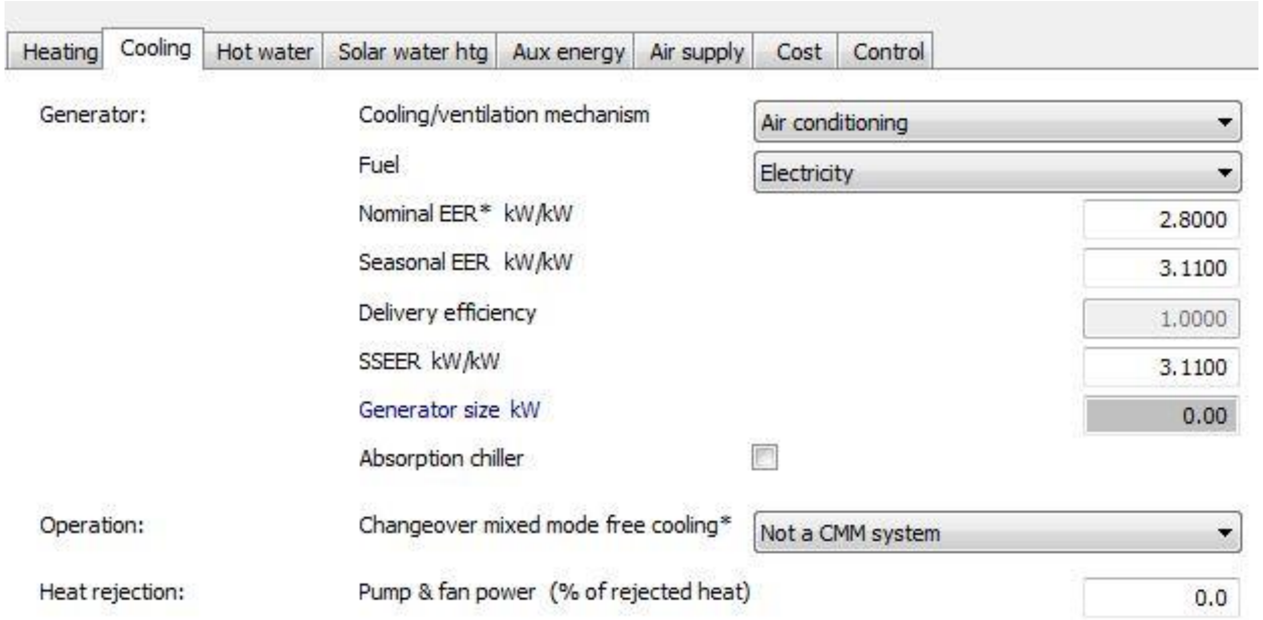
		Max latent gain	60 W/person	60 W/person	-	-	-	-	-
		Profile	daily	OFF					
	Computers	Max sensible gain	200 Watts	100					
		Max power consumption	200 Watts	100					
		Radiant Fraction	0.22	0.22					
		Profile	HVAC	OFF					
Infiltration	Max flow		Fixed infiltration: 2 ACH@50 Pa Extra infiltration: 8-20 ACH@50 Pa	1 ACH@50 Pa	1 ACH@50 Pa	0.75 ACH@50 Pa	1 ACH@50 Pa	2 ACH@50 Pa	2 ACH@50 Pa
	Profile		ON HVAC	ON	ON	HVAC	ON	ON	ON
Heating	Set-Point		19°C	19°C	19°C	19°C	19°C	19°C	19°C
	Profile		OFF	OFF	OFF	OFF	OFF	OFF	OFF

Cooling	Set-Point	22°C	22°C	22°C	22°C	22°C	22°C	22°C
	Profile	HVAC	OFF	OFF	OFF	OFF	OFF	OFF
	Seasonal EER	3.11 Kw/kW	-	-	-	-	-	-
	Nominal EER	2.8 Kw/kW	-	-	-	-	-	-
	SSEER	3.11 Kw/kW	-	-	-	-	-	-
Humidity	Humidity control	30-60	0-100	0-100	0-100	0-100	0-100	0-100

Table B-2. Roof surface characteristics.

Roof surface characteristics		**Absorptance**	**Emissivity**
Before cool roof coating	Outside	0.8	0.25
	Inside	0.15	0.05
After cool roof coating	Outside	0.125 (1-0.875)	0.89
	Inside	0.15	0.05

Table B-3. Assumptions used to model air-conditioning system.



Appendix C

Table C-1. Actual data for the selected days in the thesis.

Date	Time	Weather(BOM)	Thermometer F	Thermometer D	Thermometer E
20-Oct	0	18.8	20.94	20.7	23.2
	0.5	18.2	20.69	20.2	23.2
	1	18.3	20.44	20.2	22.7
	1.5	18.1	20.44	19.7	22.7
	2	17.8	20.19	19.7	22.2
	2.5	18.3	19.94	19.2	22.2
	3	17.9	19.94	18.7	21.7
	3.5	17.6	19.69	18.7	21.7
	4	17.3	19.44	18.7	21.7
	4.5	17.1	19.44	18.7	21.2
	5	17.1	19.19	18.7	21.2
	5.5	17.3	18.94	18.7	21.2
	6	18	19.44	19.2	21.2
	6.5	19	20.19	20.7	21.7
	7	20.3	21.19	26.7	21.7
	7.5	21.6	22.19	31.2	22.2
	8	22.8	22.94	33.2	22.7
	8.5	23.2	23.94	37.7	23.7
	9	23.9	24.69	37.7	24.2
	9.5	24.9	25.19	43.1	25.2
	10	24.9	24.44	40.7	26.2
	10.5	25.7	23.69	45.6	26.7
	11	27.1	24.19	43.6	27.2
	11.5	26.1	24.44	37.7	27.7
	12	26.5	24.69	48.1	28.2
	12.5	26.7	24.94	46.6	28.7
	13	26.3	24.94	44.6	29.2
	13.5	26.1	24.69	42.1	29.7
	14	25.3	24.69	43.1	29.7
	14.5	25.9	24.69	43.6	29.7
	15	24.3	24.69	42.1	29.7
	15.5	25	24.19	37.2	29.7
	16	25.2	24.94	34.2	29.7
	16.5	23.6	25.44	31.2	29.2
	17	24.1	25.44	29.2	28.7
	17.5	23.4	25.44	27.2	28.2
	18	22.7	24.94	25.7	27.7
	18.5	22.4	24.69	24.7	27.2
	19	22.3	24.44	24.2	26.7
	19.5	22.4	23.94	23.7	26.2

	20	22	23.44	23.2	25.7
	20.5	21.8	23.44	22.7	25.7
	21	21.6	23.19	22.7	25.2
	21.5	21.3	22.94	22.2	25.2
	22	21.1	22.44	21.7	24.7
	22.5	20.8	22.44	22.2	24.7
	23	20.7	22.44	22.2	24.2
	23.5	20.4	22.44	22.2	24.2
Date	**Time**	**Weather(BOM)**	**Thermometer F**	**Thermometer D**	**Thermometer E**
20-Dec	0	18.4	22.44	22.2	25.2
	0.5	18	21.94	21.7	24.7
	1	17.7	21.94	21.2	24.7
	1.5	18.6	21.44	21.2	24.2
	2	18.1	21.44	21.2	24.2
	2.5	18	21.44	21.2	24.2
	3	18.5	21.19	21.2	24.2
	3.5	18.3	21.19	21.2	23.7
	4	18.4	21.19	21.2	23.7
	4.5	18.4	21.19	21.2	23.7
	5	17.9	21.19	21.2	23.7
	5.5	18.4	21.19	21.2	23.7
	6	19.6	21.19	21.2	23.7
	6.5	20.7	21.69	21.2	23.7
	7	22.2	22.19	21.7	23.7
	7.5	23.3	22.94	22.2	23.7
	8	24.9	23.69	24.2	24.2
	8.5	24.9	24.44	25.2	24.2
	9	26.9	24.19	26.7	24.7
	9.5	27.4	23.69	27.7	25.2
	10	27.4	23.69	26.7	25.7
	10.5	26.9	23.94	27.7	25.7
	11	27.6	23.69	27.7	26.2
	11.5	27.8	23.94	27.7	26.2
	12	27.8	23.69	28.7	26.7
	12.5	28.1	23.69	31.2	26.7
	13	27.4	24.19	29.7	27.2
	13.5	27.7	23.94	31.7	27.7
	14	27.8	23.94	29.7	28.2
	14.5	27.8	23.94	30.2	28.2
	15	27.5	23.94	31.2	28.2
	15.5	27.3	23.94	31.7	28.7
	16	27	23.94	30.7	28.7
	16.5	27.2	23.94	30.2	29.2
	17	26.6	23.94	29.7	29.2
	17.5	26	23.69	29.2	29.2
	18	25.4	24.94	28.7	29.2

18.5	24.6	25.19	27.2	28.7
19	24.1	24.94	26.2	28.2
19.5	23.9	24.94	25.7	28.2
20	23.7	24.44	25.2	27.7
20.5	23.5	24.44	24.7	27.7
21	23	24.19	24.7	27.2
21.5	23	23.94	24.2	27.2
22	22.8	23.94	24.2	26.7
22.5	22.9	23.69	23.7	26.7
23	22.8	23.44	23.2	26.2
23.5	22.4	23.44	23.2	26.2

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